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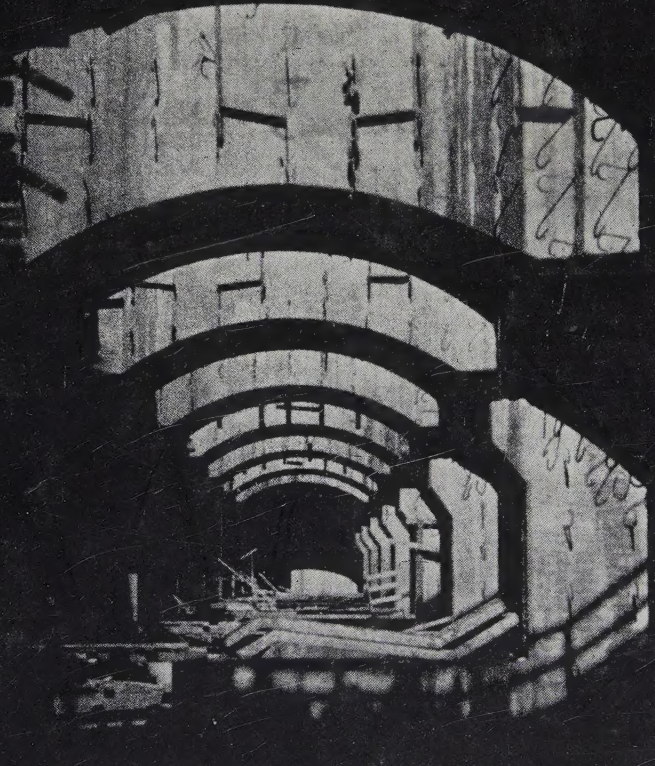
1935



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Front Cover

At Boulder Dam. A lengthwise view of the interior of one wing of the power house, at the turbine evel. Water from the turbines to be installed here will discharge through the openings at the right. Note top of dam

Photo by D. M. Simmons (F'28)

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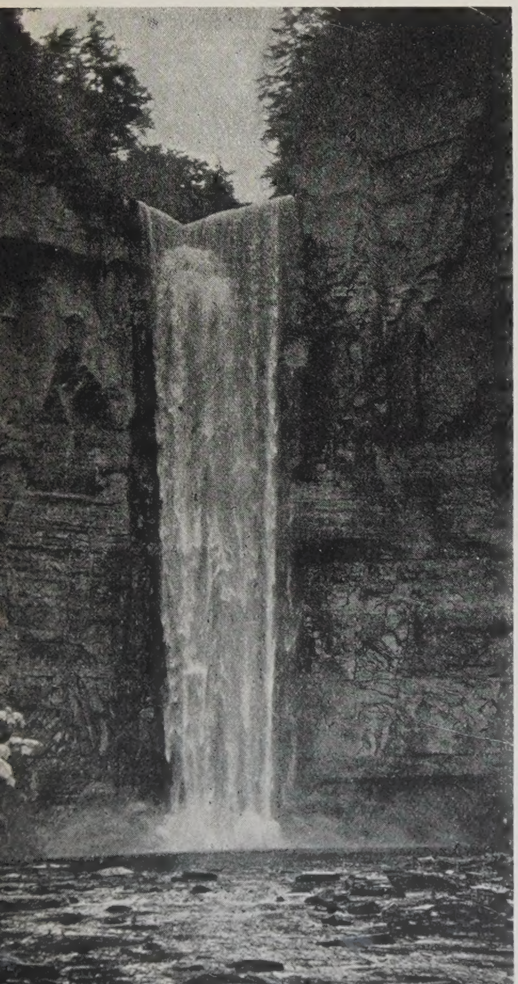
The Great Fall of Taughannock

This gorge, in Taughannock State Park, is about 11 miles from Cornell University, Ithaca, N. Y. The top of the fall is 215 feet above the man shown standing on the rocks at the right. The Institute's 51st annual summer convention will be held on the campus of Cornell University, June 24–28, 1935.



WITH a dam reaching more than $^{1}/_{10}$ mile above the natural water level of the river and more than $^{1}/_{4}$ mile long at the crest, the combination flood control, water conservation, and power development on the Colorado River known as the Boulder Canyon Project represents one of the outstanding engineering achievements of its kind. The reservoir will be 115 miles long and will have a capacity of 30,500,000 acre-feet. The power plant, half of which is in Arizona and half in Nevada, ultimately will contain 17 main generating units with a total capacity of 1,317,500 kva; initially 5 units will be installed with a total capacity of 370,000 kva. Power will be transmitted to several municipal and privately owned power systems over specially built lines. A brief review of historical facts leading up to the project appeared in the April 1935 issue (*pages 361–5*). Engineering features of the 2 275 kv lines that will transmit power to the City of Los Angeles, Calif., are discussed in this issue (*pages 494–512*); circuit breakers of the impulse type developed especially for this line were described in the April issue (*pages 366–72*). A paper on the engineering features of the dam and power house is scheduled for publication in the June issue, and one outlining the method by which sag and tension calculations were carried out in designing the several steep transmission line spans between the plant and the canyon rim is scheduled for early publication. A group of pictures depicting various phases of the project during the constructional period is included in this issue (*page 567*).

ECONOMY is one of the features stressed in making arrangements for the Institute's 51st annual summer convention to be held on the campus of Cornell University, Ithaca, N. Y., June 24–28, 1935. In addition to the low priced college dormitories and cafeteria, the customary hotel accommodations are available to those who wish them. It has been termed "a summer convention for the entire Institute." The technical program is extensive; discussion conferences, a new feature, have been scheduled; and attractive entertainment features are made possible by the location chosen. *pages 560–4*

INDUCTION motors come in for their share of attention in this issue, one of the papers presenting a general method of mathematic analysis of induction motor phenomena, giving special attention to short-circuit problems (*pages 526–9*); and the other considers d-c braking of induction motors, outlining the fundamental principles involves in this method, and presenting a simple means of calculating the current and wattage necessary *pages 488–93*

IN calculations on synchronous machines, various types of reactances are used. Magnetic saturation in the machine is shown to have an effect on the values which should be used for these reactances, and saturation factors for the more important constants used in transient and unbalanced load conditions, based upon actual short-circuit tests on a large number of machines, have been made available in curve form. *pages 545–50*

DURING the last 30 years, the use of electric power equipment in steel plants has increased rapidly. Extensive installations of power generation and distribution equipment have been made in steel plants, and many large sized generating units are used. Electric motors were applied first to auxiliaries, but are now used also for main mill drives; synchronous motors and d-c motors largely have superseded induction motors for this purpose. *pages 481–5*

THE satisfactory charging of storage batteries requires a knowledge of the proper rate at which to charge a battery, and the determination of the proper point at which to stop the charge. Observation of gas evolution, acid concentration, heating, and "local action" may be used to determine proper methods of charging. Automatic as well as manual control may be used in several different charging schemes. *pages 516–25*

TIME - TEMPERATURE tests frequently provide a convenient method of measuring losses in electrical machines. The method, although most frequently used in connection with turbine generators, can be applied to practically all types of electrical apparatus. These losses are determined from the initial slope of the time-temperature curve immediately after a load is thrown off. *pages 512–5*

WITH cheaper capacitors available, an induction generator with capacitive excitation, which has load-voltage characteristics similar to those of a d-c shunt wound machine, offers attractive possibilities. Recent tests show that such a machine may be operated independently at a predetermined voltage and frequency with good wave form. *pages 540–5*

THERMAL expansion of a liquid in a closed system actuates the mechanism in an improved electrothermic instrument for measuring various electrical quantities. It is not subject to the errors inherent in bimetallic strip instruments, and it has a linear input-deflection characteristic. *pages 474–81*

BY means of stroboscopic light of great instantaneous intensity and a moving-film camera the power angle of a synchronous machine can be recorded directly. This method was developed particularly for studying the transient performance of machines during system disturbances. *pages 485–8*

THE Engineers' Council for Professional Development recently published its second annual report, outlining past accomplishments and plans for the future with regard to student guidance, accrediting of schools, professional training, and improvement in professional status of the engineer. *pages 568–9*

TRANSMISSION engineers may find useful a set of hyperbolic function charts covering line lengths from 0 to 290 miles (for 60 cycle lines). *pages 550–4*

Engineering Education Needs a "Second Mile"

By WILLIAM E. WICKENDEN, Member A.I.E.E.
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The demand for strictly professional engineering service will diminish in volume but will rise sharply in its qualitative standards, while the demand for quasi-professional services will increase markedly. This is one of the opinions voiced by Doctor Wickenden in a recent address,* full text of which is presented herewith. In order to prepare men to furnish these services most effectively, he concludes that their education should consist of a common matrix of 3 years, with a terminal year for men who purpose to enter the general service field, and a longer period of more profound and generalized scientific studies for those who aspire to the professional field—not a separate route for the purely professional engineer, but a "second mile."

HOW can industry be supplied with trained man power adequate for its producing, distributing, and service functions, and the engineering profession advance to a properly restricted and selective status? Can the same machinery of recruitment and education serve both ends? The occasion for a discussion of these questions arises from an increasingly urgent campaign not only to restrict by law the practice of engineering, but also to reduce the number of future applicants for this privilege by limiting admissions to engineering colleges. The avowed aim of this campaign is wholly praiseworthy—to safeguard the professional and economic position of the engineer and to advance his claim to the esteem and confidence of the public. The licensing of engineers is already an accomplished fact in a majority of states and presumably soon will prevail in all. For the present, at least, this issue has passed out of the realm of argument. The campaign for restriction of college enrollments is only beginning.

Appealing to the law of supply and demand, as the key to social and economic status, the advocates of restriction clearly imply that the open doors of the colleges are a direct menace to the profession. The argument is supported by assuming a close parallel between engineering and certain other professions. In my opinion the parallel is not valid, and a policy of purely numerical restriction applied at college doors is short-sighted, narrow in perspective, and likely to injure the engineering profession in the long run, whatever the immediate benefits to a minority.

In the present emergency every profession is seeking to make its status more secure. The threat or reality of unemployment, the stress of competition, the spur of ambition, the advance of knowledge, the growth of specialization, the universal sense of social insecurity—all contribute to this concern. Teachers, librarians, social workers, personnel executives, and secretaries of welfare organizations, whose place in the professional hierarchy never has been too secure, exhibit this concern in fairly acute degree, and older and more traditional groups but little less so. The medical profession, firmly entrenched in its legal privileges, secure in its restriction of numbers, and high in prestige as a result of brilliant technical progress, has become the standard by which every other group measures its position. The strict limitation of admissions, applied at the doors of medical schools has contributed so conspicuously to the welfare of the medical profession that now many engineers are tempted to pay the tribute of imitation. We are reminded that in 1906 there were 162 approved medical colleges in the United States, while in 1930 there were only 76; that in 1905, there were 26,147 medical students, while in 1920 there were but 13,798; that in 1905, the medical schools turned out 5,606 graduates, but that by 1919 this number had been reduced by more than half, to 2,656; and that in 1904, 4,700 physicians were added to the profession, while in 1918 the new admissions had fallen to 2,975. I do not question these figures, they are presumably accurate; I do not question the benefits conferred upon both the medical profession and the public. What I question is the intimation that the engineering profession should have done likewise.

The contrasts in status and function between the engineer and the physician are so great that the supposed parallel is without validity. Medicine, as everyone knows, is one of a group of professions that serves individuals in personal emergencies. The incidence of these emergencies in a population living on a given social level is quite well known and determines the number of persons a single physician can serve effectively. Inevitable inequalities in distribution and service must be allowed for, but an optimum quota, or ratio of physicians to population is easy to establish. An increase in physicians beyond this quota does not insure superior service nor does it contribute to medical progress; on the contrary, it merely multiplies the temptations to exploit human ignorance and frailty, on the plea that surplus practitioners must live, somehow. Competition may be the life of trade, but it is the death of good medical care. Furthermore, medicine is a sharply bounded calling from which few men are called by choice or circumstance to other careers; nor are there any easy gradations of authority to keep a career open to talents. Every French private, according to Napoleon, carried a marshall's baton in his knapsack, but no hospital orderly is permitted the illusion that he may somehow rise to rank of chief surgeon.

* One of 4 addresses delivered at a forum on "Scientific Education—What Is Wrong With It?" held by the New York Electrical Society, New York, N. Y., March 29, 1935.

Merely to state these facts suffices to make clear the contrast between medicine and engineering. Engineers seldom serve individuals, nor is their concern the relief of personal emergencies; instead they serve society through its corporate agencies and in its constructive enterprises. No statistician can state the incidence of these constructive needs; their number is not limited inherently, nor does engineering progress tend to restrict or eliminate them, as medical progress aims to banish disease. Rather, all engineering progress tends to widen the domain of engineering. No one can set an optimum quota of engineers for a given population nor prove that a sharp restriction of their numbers is necessary for public welfare and safety. To have fewer engineers does not necessarily imply better engineers, so long as their work lies principally in areas of competitive enterprise.

Technical progress in engineering apparently is little affected by over-crowding, except as the "horse sense" of one generation is unable to compete successfully with the science of the next. This condition was easily observable during the past decade in Germany, where a surplus of nearly 200,000 in the technical professions is reported to have been built up, as young men fresh from the universities rapidly were absorbed at the bottom and older men who had not kept abreast of their professions gradually were crowded out. To create and protect a partial monopoly for these men would have been in their personal interest, but not in the interest of scientific advance.

Engineering Not a Caste

The relation a profession bears to associated groups is especially pertinent to this matter of restriction. The profession of medicine is by law and tradition a caste; sharp, closed boundaries separate it from all other groups that touch on its functions. The profession of engineering is not a caste, but a vaguely bounded nucleus within a large body of technical workers. No wall separates them as a membrane divides the yolk from the white of an egg. The gradations of function are imperceptible. The professional nucleus continuously is drawing into itself much of the superior talent in the outer mass, on the one hand, and on the other continuously sending out men into almost purely executive functions. Close these free paths of interchange between professional, executive, commercial, and producing groups, and in my opinion, the engineering profession quickly will sterilize itself.

Technical education, in its broader sense, conceivably might be overdone, but actually it never has been. Who is competent to fix an arbitrary limit to those who should be trained to use Stephen Van Rensselaer's historic phrase, "in the application of science to the common purposes of life"? In America, at least, we certainly have not overdone education in applied science. At the highest estimate, less than $^1/_3$ of the posts in industry that could be filled with gain to society by persons who had completed a substantial scientific or technological education, have been so filled under normal business conditions. If we were to go one step further down in the scale of organization and include in our estimate the higher levels of foremanship as well as the general planning and supervisory forces, the potential outlet in industry for technical education would be doubled or trebled.

This brings us to the heart of our problem. What relations should exist between these general service needs of industry and the selection and training of the inner nucleus of professional engineers? Should separate provision be made for each, or should one be an outgrowth and extension of the other? All engineers desire to see the inner professional body advance in public esteem and influence, and to see it enjoy sufficient security and compensation to attract men of high talent and character. This inner body, we recognize, is not coexistent with any existing organization. Probably some more exact and advanced code of educational qualifications should be its chief distinguishing feature, since the gradations from professional to executive and commercial functions are so imperceptible. Merely to distinguish between publicly licensed engineers and others is not enough—a true profession is still too much a thing of the spirit.

Two Types of Technological Education?

Returning now to ways and means of education, why not separate higher technological education into 2 quite distinct compartments? In one, train men for purely professional work as engineers; in the other, provide training of a more elastic character for the general service needs of industry? Whatever the abstract merits of the idea, the practical difficulties of converting the existing educational machinery to this dual function are fairly forbidding. The experience of such engineering colleges as have sought to become professional schools in this strictest sense is not reassuring. Enrollments have fallen, costs have risen, and the problem of maintaining a sufficient scope and volume of work to support an adequate specialized faculty has become acute. However, is the idea of segregation sound in principle? How is a young man to determine in advance whether he belongs in the professional nucleus of engineering or in its general service functions? Will he find it out by prolonging his preliminary education in an arts college? Can any vocational counselor or tester make the choice for him? Would employers of engineers respect it? I doubt it.

Supposing the segregation could be made, however, would it be beneficial to future professional engineers to train them as a caste apart? Is not the presence in industry of a great body of scientifically intelligent and technically competent men an essential condition on which the purest of professional engineers must rely for the execution of his plans and schedules? Must not these 2 groups speak the same language, or understand each other sympathetically? Would a caste system of education work to that end? Can the division of functions come through any other process than natural selection at a mature age?

I suspect that those who are intent on restriction and exclusion as means of raising the professional status of engineering are tempted by narrow self-

interest to forget what the nation has at stake in maintaining the numerical strength of the great quasi-professional body of those who now call themselves engineers. In the struggle for industrial supremacy, as in war, victory is likely to be on the side of the heaviest battalions. A lack in the professional nucleus can be compensated for in large part, as we have done in America, by importing highly trained men from abroad and by drafting men from the realm of pure science; but a deficit in the quasi-professional group in service functions cannot be met by improvisation, as Russia has learned to her regret. Each year sees American engineering grow more self-sufficient. With present standards of advanced training we are virtually free from the need of importing talent. Fortunately, we remain free from the fetters of caste. We still are able to assimilate the research scientist, to upgrade men from the ranks, and to match ingenuity in invention, adaptation, and production with refinement in design.

Doctor Wickenden

The best evidence available seems to indicate that the total demands on technological schools of all levels will continue to increase, though possibly the rate of increase will diminish. More young people will want this type of education and industry will continue the process of upgrading its general service forces by recruits from engineering colleges. In predicting future demands from past, 3 controlling influences that have been dominant in the last half century deserve critical attention: (1) the building up from rudimentary levels of a vast system of mineral production, manufacturing, transportation, and communication; (2) the rapid growth of urban population and the resulting development of public works; and (3) the progressive replacement of an older generation of self-trained engineers by younger men of better scientific education. The coincidence of these forces in recent decades is reflected in the age distribution of our present body of engineers, with a concentration above normal between the ages of 25 and 45.

The pace of sheer expansion in industry, urban development, and population almost certainly is diminishing. Replacement demand, pure and simple, is likely to be relatively small for 2 decades to come. We appear to have passed for a time beyond the era of original plant construction and to have entered upon a stage of progressive refinement. When all the controlling factors are considered, it seems safe to estimate that the demand for strictly professional engineering service will diminish in volume, but will rise sharply in its qualitative standards. However, the demand for quasi-professional business activity in producing, distributing, and adapting technical goods and services may be expected to increase markedly.

While an actual division of the field of engineering education between 2 types of colleges is seemingly impossible, it must be admitted that we are actually at the limit of our ability to accommodate a single educational program to both our professional and our general service objectives. A 4 year undergraduate course rapidly is becoming totally inadequate as preparation for engineering service of a high professional type, yet it remains for the present a reasonably adequate basis for the great body of service activities for which young engineers are in active demand. It is, in fact, as advanced a type of education as industry and business in general are now able to capitalize. Furthermore, it approaches close to the saturation point for the great body of engineering students. A 5 or 6 year course for all students seems not only unwarranted and unwise, but highly desirable for a considerable minority, and virtually imperative for a selected few.

What the American engineering college offers its undergraduate students is more properly called functional rather than professional education. Judged by this standard it probably is not surpassed in its effectiveness by any other undergraduate program. Its inadequacy as a professional discipline is scarcely open to question. In the present state of training and guidance, it seems inevitable that much of the process of selection between professional and general service objectives must fall within the college period rather than precede it. A common matrix of 3 years, as broadly humanistic and scientific as possible and only moderately differentiated between the major branches of engineering, should suffice for this phase of preliminary selection. For men who purpose to enter the general service field, a terminal year, about equally divided between business subjects and some major technical division of engineering may be provided, while those who aspire to the professional field may pass at this point into a longer period of more profound and generalized scientific studies, with adequate attention to the techniques and problems of research, design, and application and with due consideration of professional relations and ethics.

In a word, my ideal of professional education for engineers is not a separate route, but a second mile. In setting qualifying standards for the latter stage, all socially needful restrictions may be applied. The profession may sit as judge of standards and objectives without putting the colleges into a straight jacket. The Engineers' Council for Professional Development is adapted admirably to this function. In time, the standards of attainment it may set for full professional recognition may make public licensure of relatively nominal significance. Meanwhile the solidarity of the greater engineering fraternity may be preserved for the ideals of democracy and the larger service to our common life.

An Improved Electrothermic Instrument

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An improved electrothermic instrument for measuring watts, amperes, or volt-amperes, actuated by the thermal expansion of a liquid in a closed system which includes a Bourdon tube, is described in this paper. The new instrument is not subject to the errors inherent in the bimetallic strip type of electrothermic instrument, it has a linear input-deflection characteristic, and its time period may be adjusted readily to any desired value up to at least 60 minutes.

IN 1915 the writer contributed a paper[1] to the A.I.E.E. describing a method of measuring watts, amperes, and volt-amperes by electrothermic methods. In 1918, a second paper[2] was contributed setting forth in some detail the characteristics of a wattmeter built according to the principles set forth in the 1915 paper. The electrothermic demand meter described in the writer's 1918 paper was introduced into Canada a year later, where it now is widely used. It was not introduced into the United States until 1928. In 1929 a third paper[3] was contributed describing how the principles enunciated in 1915 could be applied to the totalizing of system loads so that load measurements at widely separated points on an electric system might be added automatically and indicated or recorded at one central point. It is the object of this paper to describe still further developments of the principles enunciated in the 1915 paper. These developments have led to an improvement in the electrothermic instrument, based primarily upon securing a first-power law for the heat loss that necessarily takes place in any instrument of this type. This first-power law for heat loss is responsible for an accuracy of measurement that is utterly unattainable with the present construction.

Shortcomings of Bimetallic Strip Instrument

The electrothermic instrument as now built is described fully in the writer's 1918 paper already referred to, and no further description is incorporated in this paper. There are certain shortcomings in the device as now built of which the writer long has been aware. There are 4 deficiencies in the present construction which the writer has been endeavoring to eliminate for many years and which the construction described later in this paper does eliminate. These are: temperature error, power factor error, lack of scale uniformity, and lack of torque in the moving element.

While the temperature error of the existing bimetallic strip instrument is within the meter code requirements, there is nevertheless an appreciable temperature error. Means for correcting the temperature error in the existing construction are now available. This correcting means, however, is aimed at the symptom and not the cause. The new construction described in this paper eliminates the cause.

The reason for this temperature error is not hard to find. As is well known, a hot body may lose its heat in 3 ways: by radiation, by convection, and by conduction. Each of these methods of heat dissipation follows a different law. Radiation follows the well-known Stefan-Boltzman law. In figure 1 may be found the mathematical expression for this law and a graphical presentation of the losses per square centimeter for the 3 ambient temperatures, −40, 0, and +40 degrees centigrade. The differences in the radiation loss at different ambient temperatures account for most of the temperature error in the existing bimetallic strip type of instrument.

When the instrument was first manufactured, it was hoped that this variation in radiation loss with

Loss by radiation is defined by the Stefan-Boltzman law:
$J = 3.00 \times 10^{-12} (T_1^4 - T_2^4)$
in which
J = watts loss per square centimeter
T_1 = absolute temperature of hot body
T_2 = absolute ambient temperature
Watts loss by convection is defined by the theoretical Rice formula: $W_c = 0.00066 \frac{(\Delta t)^{1.25}}{T_{ave}^{0.123}}$
in which
W_c = watts loss per square centimeter
Δt = temperature rise of hot body
T_{ave} = absolute temperature (average) of hot body and ambient air

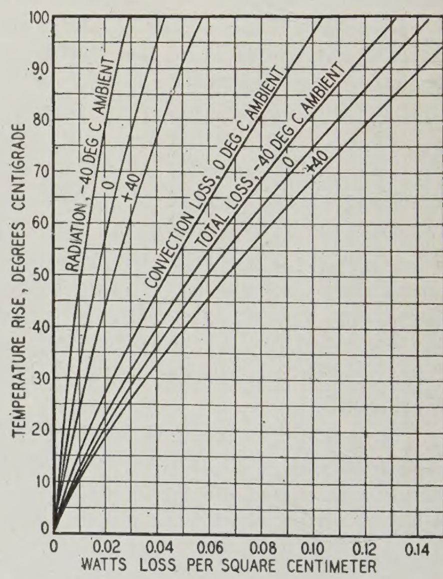

Fig. 1. Watts loss by radiation and convection per unit area of a body

A paper recommended for publication by the A.I.E.E. committee on instruments and measurements, and scheduled for discussion at the A.I.E.E. summer convention, Ithaca, N. Y., June 24–28, 1935. Manuscript submitted June 27, 1934; released for publication March 8, 1935.

1. For all numbered references see list at end of paper.

ambient temperature could be made negligible by using polished surfaces for the parts where heat was dissipated, but it was found that the permanence of a polished surface could not be depended upon. For "black body" radiation the constant in the Stefan-Boltzman law given in figure 1 is 5.75×10^{-12} (not 3×10^{-12} as there given), and it was found that permanence could not be depended upon for values of this constant less than about 3×10^{-12}. Permanence for radiation losses cannot be assured with a smaller value of this constant.

In the matter of heat loss by convection, the best data available at the time of the preparation of the writer's 1915 paper indicated that this loss was directly proportional to the temperature rise of the hot body above the ambient air. Since that time much new light has been shed on convection losses. Probably the most authoritative information now available is the work of Chester W. Rice reported[4] in 1924. According to his findings, convection loss varies *not* with the first power of the temperature rise of the hot body, but with the 1.25 power; it also varies very gradually with the ambient temperature (see theoretical Rice formula in the subcaption of figure 1). Figure 1 gives a curve showing the convection loss per square centimeter from a small cylinder calculated from the data given in the Rice paper. This curve is calculated for an ambient temperature of 0 degrees centigrade; the ambient temperature may depart from this assumed value by some 40 or 50 degrees in either direction without changing the resultant convection losses by more than 2 or 3 per cent. Figure 1 shows also the total losses

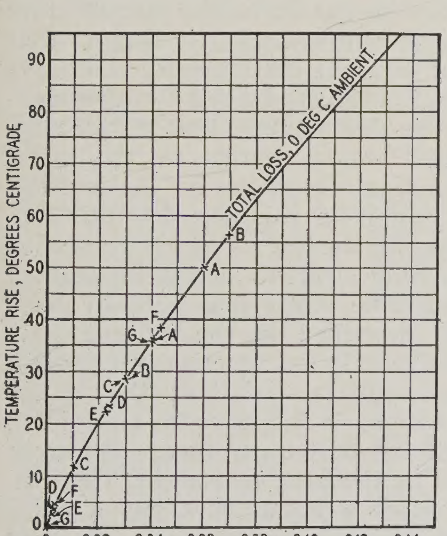

Fig. 2. Total-loss curve for ambient temperature of zero degrees centigrade of figure 1; points A to G indicate differential wattages corresponding to data in table I

Curve	Per Cent Full Load	Power Factor
A	50	0.25
B	100	0.50
C	50	0.50
D	50	0.75
E	50	1.00
F	100	0.75
G	100	1.00

of heat from a hot body resulting from convection and radiation combined; that is, to the convection loss values are added the corresponding values of the radiation loss giving 3 resultant total loss curves for the 3 ambient temperatures, −40, 0, and +40 degrees centigrade.

In the matter of heat loss by conduction, this follows strictly a first-power law. If the heat flow takes place through copper, as it does in an electric meter, there is the advantage of a very low temperature coefficient for thermal conductivity (−0.013 per cent per degree centigrade).

In the writer's 1915 paper it was proved that the instantaneous temperature difference between 2 similar bodies A and B when heated electrically by the methods described in that paper is given by the expression:

$$\theta_1 - \theta_2 = \frac{H_1 - H_2}{SE + 2Q}\left(1 - \epsilon^{\frac{-(SE+2Q)t}{M}}\right) \qquad (1)$$

where

θ_1 = instantaneous temperaure of A above ambient temperature
θ_2 = instantaneous temperature of B above ambient temperature
H_1 = rate in gram-calories per second at which heat is applied to A
H_2 = rate in gram-calories per second at which heat is applied to B
Q = thermal conductivity of thermal shunt in gram-calories per second per degree centigrade temperature difference
E = heat emissivity of A or B in gram-calories per second per degrees centigrade per square centimeter of surface (similar)
S = surface area in square centimeters of A or B (similar)
M = amount of heat in gram-calories stored in A or B per degree centigrade of temperature rise (similar)
t = time after beginning heat application, in seconds
ϵ = base of Napierian logarithms = 2.718+

It might be pointed out further that equation 1 was derived on the assumption that all heat losses were first-power functions of temperature. It was proved further that with the arrangement of circuit as shown in that paper, the quantity $H_1 - H_2$ is always proportional to watts, independent of power factor and wave form. It was recognized at the time of presentation of the 1915 paper that if radiation were permitted to become an appreciable factor, some error would result; but it was believed that radiation could be made negligible by proper treatment of the surfaces of the heat radiating parts of the instrument. This hope was not realized. It was further believed in 1915 that convection loss from a hot body was a first-power function and it was not until Rice presented his classical paper in 1924 that this belief also was dissipated. In this connection, it is interesting to note that Rice himself in a preliminary paper presented in 1923 still held at that time to the first-power law for convection loss.

Causes of Temperature and Power Factor Errors

In the light of this new information, the results of which are presented graphically in the curves of figure 1, a very casual analysis shows the reasons for both the temperature and power factor errors of the electrothermic instruments as previously built. It is obvious at once from an inspection of the curves of figure 1 that a given differential wattage application to the 2 elements of the instrument will not cause the same differential temperature, but that this differential temperature itself will vary with ambient temperature. For instance (see figure 1) 0.05 watts per square centimeter will cause a 39.5 degree temperature rise when the environment temperature is +40 degrees and a 47.0 degree temperature rise when the ambient temperature is −40 degrees. This is a difference of approximately 16.0 per cent

Table I—Watts Applied to the 2 Elements of an Electrothermic Wattmeter for 2 Values of Circulating Current

Circulating Current	Per Cent Load	1.00 Power Factor			0.75 Power Factor			0.50 Power Factor			0.25 Power Factor		
		$\frac{I}{2}$	a^2	b^2	$\frac{I}{2}$	a^2	b^2	$\frac{I}{2}$	a^2	b^2	$\frac{I}{2}$	a^2	b^2
50% of unity power factor full load current = 0.5 amp	0	0.0	0.2500	0.2500	0.0	0.2500	0.2500	0.0	0.2500	0.2500	0.0	0.2500	0.2500
	50	0.25	0.5625	0.0625	0.3333	0.5833	0.0833	0.5	0.7500	0.2500	1.0	1.5000	1.0000
	100	0.50	1.0000	0.0	0.6667	1.1667	0.1667	1.0	1.7500	0.7500	2.0	4.7500	3.7500
125% of unity power factor full load current = 0.795 amp	0	0.0	0.625	0.625	0.0	0.625	0.625	0.0	0.625	0.625	0.0	0.625	0.625
	50	0.1580	0.900	0.400	0.2110	0.919	0.419	0.3160	0.975	0.475	0.632	1.275	0.775
	100	0.3160	1.225	0.225	0.4220	1.303	0.303	0.6320	1.525	0.525	1.264	2.725	1.725

Watts loss in meter element A proportional to a^2; in element B, b^2.

for an 80 degree temperature change or approximately 0.2 per cent per degree centigrade. The temperature error thus calculated agrees closely with that observed. The method proposed for eliminating this radiation error is indicated by the construction shown in figures 4 and 6 and is discussed further later in this paper.

The source of the power factor error also is obvious from the foregoing analysis. The reason for this error is that the watts loss versus temperature rise relation is not linear. It might be pointed out further that the observed power factor error is essentially a temperature error. By reference to table I, it may be noted that while the *differential* watts applied to the 2 heaters of the electrothermic instrument is always proportional to watts and independent of voltage, frequency, wave form, and power factor, the actual watts applied to each heater increases as the power factor departs from unity whether lagging or leading.

In order to determine the order of the power factor error in the electrothermic instrument, the total-loss curve for an ambient temperature of 0 degrees centigrade of figure 1 is reproduced in figure 2. On this curve are indicated the positions of the differential wattages corresponding to various loads and power factors. These differential watts are taken from table I on the assumption that the differential watts per square centimeter at 50 per cent load are 0.02 and at 100 per cent load 0.04. From this analysis it is obvious that the power factor error is well within the meter code limits at the loads and power factors specified in the code. However, as heavier loads are applied at lower power factors, the error rapidly becomes greater. For instance, the theoretical error, as determined by the foregoing method of analysis, at full load and 0.5 power factor (double full load current at unity power factor) is of the order of 20 per cent. The actual error under test is only about 4 per cent. Most of this theoretical error is eliminated by properly proportioning the meter scale, that is, by contracting it at the upper end. It is evident therefore from the foregoing analysis that the power factor error in the electrothermic instrument is caused by the departure of the watts versus temperature rise curve from a straight line.

A comparatively large circulating current in the electrothermic instrument is desirable. Table I shows the watts that will be applied (and therefore the approximate temperature rise) to the 2 elements of an electrothermic wattmeter when the circulating current is 50 per cent of the unity power-factor full-load current, and also when the circulating current is 125 per cent of the unity power-factor full-load current. It is obvious that the "spread" between the maximum and minimum temperatures attained by the elements of the instrument under conditions of load and power factor met in practice is lower when using the larger circulating current.

Early Experiments to Eliminate Errors

Once having determined the cause of an error, means for its elimination begin to suggest themselves. It may be of interest to describe a few of the earlier attempts to eliminate the errors observed in the electrothermic instrument and thereby to show how continued investigation and experiment finally led to the complete solution described in this paper.

As soon as it was realized that radiation losses could not be made negligible in an instrument in which permanence is essential, it was realized also that radiation losses would introduce a curvature into the watts versus temperature rise curve; that is, that there is an inherent curvature in the curve representing the relationship as defined by the Stefan-Boltzmann law. The first modification in structure that was considered was a return to the metal diaphragm construction described in the writer's 1915 paper. The reason for this was that this construction would permit the use of liquid expansion for the heat responding elements of the instrument instead of the bimetallic strips that actually have been used and as described in the writer's 1918 paper. The bimetallic strip has practically a straight line response to temperature variation; that is, the deflection (or the torque, if deflection be restrained) is directly proportional to temperature. However, if a liquid be used as the heat responding element, it is possible to select a liquid that has a rising characteristic and thereby compensate, at least partially, for the falling characteristic in the watts versus temperature rise curve. By careful selection of the liquid it was hoped to obtain complete compensation. Hundreds of liquids are available, and, by considering mixtures of 2 or more liquids, the possibilities in matter of adjustment of the expansion characteristic of a liquid become literally infinite. Later in this paper appears a table (table II) giving the expansion characteristics of a few liquids; this table, of course, contains only an exceedingly small proportion of the liquids that might have been considered.

Experiments with metal diaphragms were unsatisfactory. The principal reason for this was the impossibility, so far at least, of obtaining a sufficiently large motion with temperature variations. The only metal diaphragms available that would give the desired motion were of relatively large diameter; this in turn, meant a relatively large volume of liquid to be heated, a comparatively large watt input, and long time period. If metal diaphragm stacks of sufficiently small diameter and sufficiently great flexibility could be secured, the metal diaphragm construction might be a quite satisfactory solution. However, the difficulties of securing a solution by this method seemed to be greater than those offered by other possible constructions, and attention accordingly was turned to these other possibilities.

Experiments With Bourdon Tubes

After experimenting with many other various schemes, all of which proved abortive, attention was turned to the Bourdon tube. The use of the Bourdon tube was suggested in the writer's 1915 paper, but at that time consideration was given only to a tube in which the liquid being heated was contained within the curved portion of the tube itself. The method, now widely used, employing a bulb containing a liquid connected to a Bourdon tube through a capillary tube seemed to offer promise. This structure as manufactured by several companies was studied. The temperature of the bulb, as used in this structure, is registered by the Bourdon tube. The pressure changes developed in the bulb by temperature changes and registered by the Bourdon tube may be those of a completely filled system or those of a partially filled system. In the completely filled system, the expansion of the filling liquid develops the pressure; in the partially filled system, the vapor pressure of the filling liquid is registered. The liquid expansion principle is utilized in the thermal meter now proposed.

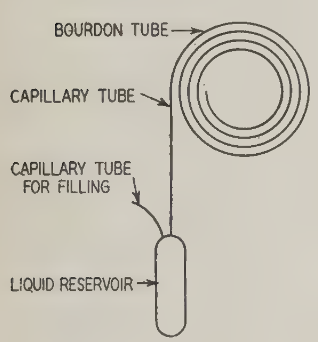

Fig. 3. A Bourdon tube with liquid reservoir for use in electrothermic instruments

The first Bourdon tubes with separate reservoirs were made by the writer in 1930, and experimentation has proceeded continuously ever since. It might be added that technical literature contains very little information concerning Bourdon tubes and it was necessary to determine by the method of trial and error the limitations of such tubes. Tubes of various materials, lengths, dimensions, wall thicknesses, reservoir volumes, spiral dimensions, etc., were tried before finally arriving at a satisfactory solution. One of the things that early became obvious was that the amount of liquid in the Bourdon tube itself should be reduced to a minimum in order that the temperature of the liquid-containing reservoir and not the temperature of the Bourdon tube itself would control the pressure within the tube.

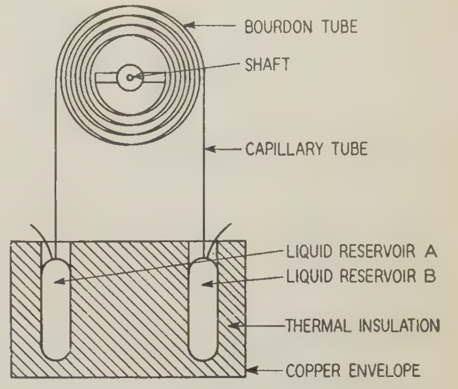

Fig. 4. Diagram of instrument mechanism using 2 Bourdon tubes with liquid reservoirs

This meant making the volume within the tube a minimum. Minimum internal volume is secured when the tube is rolled flat and this was the construction adopted. A Bourdon tube is essentially a spring, and steel is well-known to be the best available spring material. Consequently, after some preliminary experiments with other materials, steel has been used in all the writer's experimental work. Steel has the further advantage of having minimum hysteresis, being so nearly zero in the final product as to be entirely negligible. Proper heat treatment is of course important; steel is amenable to heat treatment while most other metals are not. Tubes of a material other than metal were considered, but seemed to offer no advantages.

Figure 3 shows a Bourdon tube with bulb as now proposed for use in electrothermic instruments. The Bourdon tube consists of 20 inches of $^3/_{16}$ inch steel tubing with a 0.010 inch wall. This tubing is rolled or pressed flat before being coiled into the shape shown in figure 3. After coiling, the tube is heat-treated. The liquid reservoir consists of a short length of steel tubing and is provided with hemispherical ends; its over-all inside length is approximately 1.324 inches. The capillary tube joining the reservoir to the Bourdon tube is of copper and has an outside diameter of approximately 0.06 inch; its length may be anything desired, but 4 to 5 inches have been used in the experimental models. All joints are either brazed, welded, or soldered to insure permanent freedom from leakage.

Use of 2 Bourdon Tubes

With a structure of the dimensions described, the angular motion of the Bourdon tube for a one degree centigrade change in reservoir temperature is approximately 0.8 angular degree when the tube is free, or $^1/_2$ of this value when 2 identical tubes are used opposing each other as shown in figures 4 and

6. This value is, of course, governable by the size of reservoir, type of liquid, conformation of Bourdon tubes, length of supporting arm, and many other factors. The method of using these tubes in the structure of an instrument is exactly the same as that for the bimetallic spring construction described in the writer's previously mentioned 1918 paper. The Bourdon tubes are used in pairs, these pairs being selected carefully so that they have identical characteristics in so far as their response to temperature change and torque is concerned. The inside ends of this pair of tubes are attached to a common shaft so that the 2 tubes oppose each other; that is, one tube tends to rotate the shaft in one direction and the second in the other. Thus, so long as the 2 liquid reservoirs remain at the same temperature, no matter what that temperature, there will be no rotating of the shaft; the shaft will rotate only if the 2 reservoirs are at different temperatures, and the amount of rotation is proportional to the difference in pressure developed in the 2 tubes resulting from a given difference in wattage application. If a circuit connection such as described in the writer's 1915 paper be used, a differential wattage strictly proportional to the watts of the circuit under measurement can be applied to the 2 liquid reservoirs. The problem therefore reduces to the finding of a construction that, for a given differential wattage, will cause a strictly proportional differential pressure between the 2 liquid reservoirs.

Experiments with the construction shown in figure 4 were carried out. It is obvious that this construction eliminates the errors of the earlier construction which were caused by variations in radiation losses caused in turn by variations in ambient temperature. With this construction, the exchange of heat between the liquid-containing reservoirs A and B is dependent entirely upon the rate of heat conduction through the thermal insulation, through whatever metallic connections may be installed between elements A and B, and through the lead wires and the capillary tubes. A considerable part of the heat will escape through the thermal insulation to the copper envelope and thence by radiation and convection to the ambient air. However, *differential temperature* does *not* depend in any degree upon the rate of escape of heat from the envelope except in so far as the escaping heat affects the temperature, and therefore the thermal conductivity, of the thermal insulation. It therefore becomes important to determine the temperature coefficient of thermal conductivity for this thermal insulation. All available data on this point were studied. Thermal insulators invariably were found to have a positive temperature coefficient for thermal conduction, that is, thermal conduction for a given temperature difference always increases as temperature rises. Thus, the compensation sought can be obtained if a liquid can be found with an expansion coefficient that increases at the same rate as does the temperature coefficient of the thermal conductivity in the thermal insulation. For this purpose a study was made of the characteristics of various expansible liquids.

Expansion Characteristics of Liquids

Table II contains data on the expansion characteristics of a few of the liquids considered. The data for expansion is taken from the International Critical Tables (vol. III, page 28). Many other liquids might have been considered. The last column in this table headed "excess" is a value that has been calculated on the basis of the effect of the β and γ components of the expansion curves. This value is, therefore, a measure of the amount of curvature in the expansion curve of the liquid in question. This calculation, of course, assumed that the expansion curves (see table II) may be extrapolated to 100 degrees centigrade—an assumption that may or may not always be justified.

From tests made on structures similar to that shown in figure 4 the writer has found that complete compensation can be secured. There is great latitude in the choice of available liquids, with a wide range of upward curvature in their expansion curves, and there is also a wide range of choice in heat insulating materials, with upward curvature in their temperature-thermal conductivity relations. Many combinations may be found that give

Table II—Characteristics of Some Expansible Liquids

Liquid	Expansion Coefficients (See Appendix) $\alpha\times10^{-3}$	$\beta\times10^{-6}$	$\gamma\times10^{-9}$	Temperature Range, Deg C Minimum	Maximum	Boiling Point, Deg C	Melting Point, Deg C	Excess (See Text)
Methyl alcohol	+1.0041	+1.802	+16.57	−94.5	+15	+66	−97.1	+34.4
Ethyl alcohol	+0.8461	+0.160	+8.5	0.0	80	+78.4	−114	+11.9
Carbon tetrachloride	+1.911	+0.69		0.0	40	+76	−23	+3.6
Chloroform	+1.8563	+0.6309	+8.81	−53	+55	+61.2	−70	+7.62
Acetone	+1.1142	+0.315		−83	+25	+56.5	−94.6	+2.83
Methyl ethyl ketone	+1.022	+0.46		0.0	+50	+80.6	−86.0	+4.1
Ether	+1.1044	+0.4772		−120	0	+35	−116.2	+4.32
Ethyl lactate	+1.126			+7	+108	+154.5	?	0.0
Benzene	+1.0636	+0.0376	−2.213	+11	+72	+80.36	+5.4	−1.725
Hexane	+0.8486	+1.084	−0.164	0.0	+100	+69	−94	+1.38
Toluene	+0.9159	−0.368		−95	+18	+111	−95	−4.02
Xylene	+0.8515	+0.109	+1.73	0.0	+100	+139	−53	+3.31
Cyclohexane	+0.8879	+0.972	−1.55	0.0	+65	+80.8	+6.4	+9.2
Bromotoluene	+1.25			+30	+100	+181	−26	0.0
Pinene	+0.83			+20	+293	+156	?	0.0
Tetrachloroethylene	+1.62			0.0	+90	+121	−22	0.0
Hydrocyanic acid	+1.45			0.0	+15	+25.2	−12	0.0
Ethane	+1.307			−108	−74	−86	−172	0.0
Allylene	+1.245			−55	−13	−23.5	−110	0.0

complete compensation (see mathematical analysis in appendix).

The ideal to be attained is that a given differential wattage applied to the 2 liquid reservoirs A and B in figure 4 always shall give the same angular deflection independent of ambient temperature, power factor, wave form, voltage, frequency or any other variable that may be applied to the meter. The writer's 1915 paper proved that the differential watts, using the circuit arrangement therein described, is always proportional to watts, independent of power factor and wave form, and, within reasonable limits dictated by design, can be made independent of voltage and frequency. However, a given differential wattage does not necessarily mean the same deflection at all temperatures and power factors with the instrument as built up to the present time for reasons that have been set forth. With the modifications of structure shown in figure 4, it is obvious that the temperature error in the bimetallic strip type of meter caused by radiation is eliminated since there is no radiation from each element separately. The error in the bimetallic strip type of instrument caused by the departure of the watts versus temperature curve from a straight line is eliminated not by making this curve a straight line, but by making the temperature differential versus deflection curve bend in one direction by exactly the same amount as the watts versus temperature curve bends in the other direction. Thus the watts versus deflection curve becomes a straight line and, so long as this is true, a given differential watt will cause exactly the same deflection at one part of the curve as it does at any other. Thus the error in the bimetallic strip type of instrument attributable to both temperature and power factor variations is avoided. The appendix indicates how this result may be obtained.

In addition to adjusting the temperature coefficient of the expanding liquid and of the thermal insulation, still another method of adjustment for temperature and power factor errors is available, and this lies in the selection of the thermal shunt between A and B, figure 4. A thermal shunt may be used to adjust the instrument for the desired time period. This thermal shunt, of course, should be made of metal and preferably of high thermal conductivity to curtail the amount of material used. The thermal conductivity of metals varies over a wide range; some metals have a positive and others a negative coefficient. In this respect, the metals differ from thermal insulators since the latter, as pointed out in an earlier paragraph, all have positive coefficients. Therefore, the wattage differential versus deflection relation is capable of adjustment by 3 separate methods or by a combination of all 3 of them: (1) by the selection of the expanding liquid; (2) by the selection of the thermal insulation; and (3) by the selection of the thermal shunt.

Vacuum Containers Used for Heat Insulation

As experiments were continued on the structure shown in figure 4, a still further modification seemed to offer still further advantages. This modification consisted simply of substituting for the thermal insulation of the usual type shown in figure 4, thermal insulation of the vacuum type. Heat insulation by vacuum has been known for many years. It was used first by Dewar in 1892 in connection with his classical work on liquid air. The popular thermos bottle is based upon this principle.

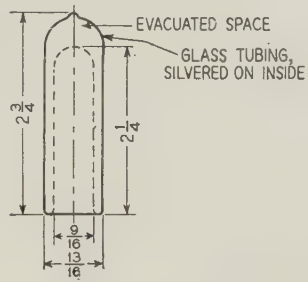

Fig. 5. Vacuum container for providing heat insulation for liquid reservoirs of electrothermic instrument

All dimensions are in inches

If, therefore, vacuum bottles be substituted for the heat insulation shown in figure 4, a structure such as shown in figure 6 will be obtained wherein the loss of heat from the liquid reservoirs A and B by convection and radiation is reduced to practically zero. This, in turn, means that the value of E (emissivity) that appears in equation 1 in the early part of this paper becomes so small in comparison to Q that E may be neglected. The ultimate temperature differential for a given wattage differential and also the time required to reach that temperature differential is then dictated almost entirely by the value of Q (thermal shunt).

Actual tests demonstrated that the time to attain a given percentage of final temperature could be varied from 10 minutes to 75 minutes simply by varying the size of leads conducting current into the heaters. Still wider range could be secured if desired.

The writer's experimental work finally led to the structure shown diagrammatically in figure 6. In this structure the heat set free in resistances A and B escapes almost entirely by thermal conduction, and the rate of escape is therefore a first-power function. The rate of heat escape is governed by the length and cross section of the thermal shunts $S1$ and $S2$, of the leads l_1, l_2, l_3, and l_4, and of the capillary tubes t_1 and t_2. The vacuum bottles are silvered on the inside and are consequently very effective heat insulators, practically free from radiation and convection losses. As would be expected, manufacturers' tests have shown the insulating properties of these bottles to be of a permanent character.

Thermal shunts S_1 and S_2 are necessary only when very short time period is required. For most purposes, the desired characteristics may be secured by adjustment of the leads l_1, l_2, l_3, and l_4. These leads serve the double purpose of electrical and thermal conductors. It may be of interest to point out that copper has not only a high thermal conductivity (3.84 watts per cubic centimeter per degree centigrade at 0 degrees), but also a low temperature coefficient for thermal conductivity (−0.013 per cent per degree centigrade).

It is this substitution of thermal conduction, a strictly first-power function, for radiation and convection, which are *not* first-power functions, that is responsible for the elimination of the curvature in the response of the Bourdon tube type of instrument to heat applications, and is therefore

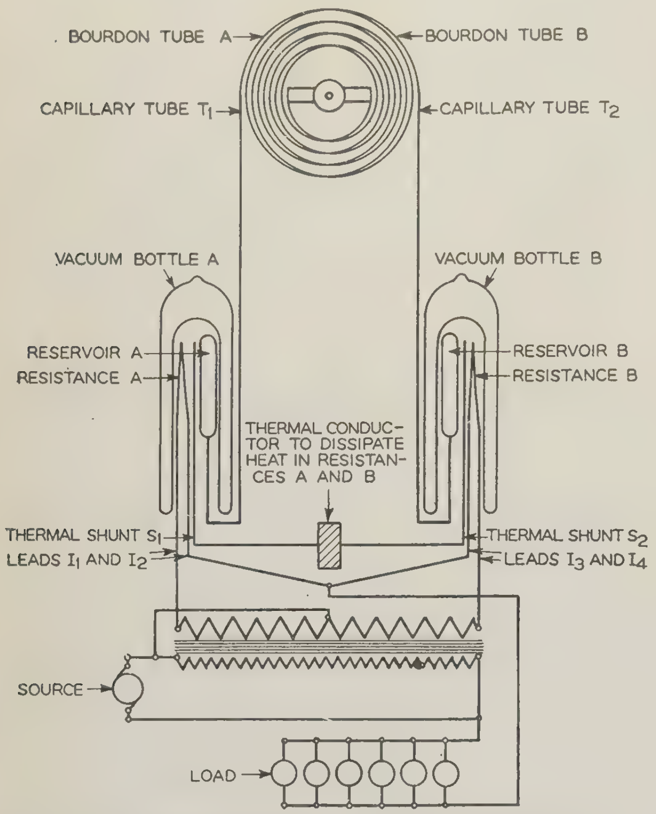

Fig. 6. Diagram showing final form of electrothermic instrument proposed in this paper, with connections to load

responsible for the elimination of the errors in the electrothermic instrument as heretofore built. The writer wishes again to emphasize particularly the importance of this first-power law for heat loss in any thermal meter.

Characteristics of New Instrument

Some of the characteristics of this new electrothermic instrument may be of interest. In the matter of torque, it has many times the torque of any previous instrument ever built so far as the writer's knowledge extends. Tests on several 500 watt instruments show a torque in excess of 300 millimeter-grams per degree of deflection of the Bourdon tubes. This means a full scale torque of 6,000 to 7,000 millimeter-grams, which is some 12 times the torque available in the bimetallic strip type of instrument.

In the matter of overloads, sample instruments have been tested at loads 4 to 6 times full load continuously without signs of distress other than charring of fibrous insulations.

In the matter of losses, tests on experimental instruments show total losses at no load of less than 2 watts including transformer losses. At full scale deflection these losses rise to somewhat less than 3 watts. Thus it may be noted that the watt losses in this new type of electrothermic instrument are of the same order of magnitude as those of the usual type of induction watt-hour meter. It should be noted particularly, however, that these losses are pure resistance losses; that is, the volt-ampere losses are the same as the watt losses. Thus, the volt-ampere losses in this new instrument are a rather small fraction of those in the usual type of watt-hour meter, and consequently its burden on potential and current transformers is correspondingly less.

In the matter of temperature rise, the new electrothermic instrument is adjusted to have approximately a 20 degree centigrade rise above the ambient air in both liquid-containing reservoirs at no load. At unity power factor, full scale (the maximum load the meter is expected to carry continuously), the temperature rise of the hotter reservoir above the ambient air is approximately 50 degrees centigrade. The differential temperature between the 2 reservoirs is strictly proportional to watts, independent of power factor and wave form. At power factors other than unity, the temperature rise of the hot reservoir is less than with the same current at unity power factor.

In the matter of voltage, power factor, and temperature variations, their effect on the indications of this new instrument is negligibly small.

In the matter of time period, this may be adjusted readily to any value desired, up to at least 60 minutes. The time period on rising loads and falling loads is the same in this new instrument. This is not strictly true with the bimetallic strip instrument. The reason for this difference is obvious; in the Bourdon tube instrument the relation between temperature and deflection is strictly a linear function, while in the bimetallic strip instrument it is not.

In this new instrument, since heat loss is strictly a first-power function, scale deflection is uniform throughout the entire range. In this respect it differs materially from the bimetallic strip instrument where the upper end of the scale is contracted approximately 12 per cent as compared with the lower end. The first-power law for heat loss further insures that this new type of instrument always will follow a true exponential law for watt applications. These features may be utilized to extend the usefulness of the meter.

Appendix—Expansion Characteristics of Liquids

The expansion characteristic of a liquid may be represented by the expression

$$V_t = V_0(1 + \alpha t + \beta t^2 + \gamma t^3)$$

where

V_0 = the volume of the liquid at 0 degrees centigrade
V_t = the volume of the liquid at t degrees centigrade
t = temperature of the liquid in degrees centigrade
α, β, and γ = constants

Similarly, the thermal conductivity of a thermal insulator may be expressed by

$$K_t = K_0(1 + \alpha' t + \beta' t^2 + \gamma' t^3)$$

Differentiating this expression for V_t and K_t with respect to t,

$$dV_t = V_0(\alpha dt + 2\beta t dt + 3\gamma t^2 dt) \quad (2)$$

$$dK_t = K_0(\alpha' dt + 2\beta' t dt + 3\gamma' t^2 dt) \quad (3)$$

Dividing equation 2 by equation 3,

$$\frac{dV_t}{dK_t} = \frac{V_0}{K_0} \frac{\alpha + 2\beta + 3\gamma t^2}{\alpha' + 2\beta' t + 3\gamma' t^2} \quad (4)$$

From an inspection of equation 4 it is obvious that $\frac{dV_t}{dK_t}$ becomes a constant when $\alpha + \beta + \gamma = c(\alpha' + \beta' + \gamma')$ where c may have any value whatever.

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Electric Power Equipment for Steel Plants

The rapid increase in the use of electric power equipment in steel plants in the United States during the last 3 decades is outlined briefly in this paper, and the principal types of apparatus now in use are discussed. Power generation and distribution equipment is considered briefly and the types of electric motors used in different kinds of main mill drives are outlined. Synchronous motors and d-c motors are shown to have largely superseded the use of induction motors.

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THE history of the electrification of the steel industry in America covers a period of little more than 30 years. Between 1905 and the present, American manufacturers have furnished main drive motors for steel plants having a total continuous capacity of 2,850,000 horsepower. Of this capacity, 85 per cent has been supplied since 1915. Because of the rapidity of this development and the wide variety of electrical equipment used, the story of the electrification of the steel industry forms an interesting chapter in the history of American industry.

Years before the use of electricity in industrial operations, the iron and steel industry was a large user of high capacity power units. When wrought iron was giving way to steel, power requirements increased and the low capacity, unflexible water wheel was abandoned in favor of steam power. The reciprocating steam engine and the rolling mill rapidly grew up together, each successive installation pointing the way to the use of heavier mills and more powerful engines. By 1890 the manufacture and servicing of rolling mill engines had become a flourishing business. One builder alone supplied 294 engines to the iron and steel industry.

The most spectacular units produced by the engine builders were the large reversing engines for driving reversing blooming, slabbing, and plate mills. The most advanced types were 4-cylinder, twin, tandem-compound units, some of which were capable of exerting 15,000 peak horsepower. When operated condensing, the steam consumption of these units alone was not excessive for conditions existing at that time. Their simplicity and large size and the smoothness and apparent ease with which they worked inspired confidence in the hearts of rolling mill men. At first these men were loath to place the same confidence in the smaller and less spectacular, but more powerful, reversing motor.

Gradual Adoption of Electricity

During the development of the reciprocating engine for main roll drive, the mill auxiliaries were driven by small non-condensing engines or by hydraulic mechanisms. These drives were inherently inefficient and their excess steam consumption, together with the losses in the complex system of steam lines necessary for their operation, seriously affected the over-all economy of the power system. Therefore, the first major step in the electrification of iron and steel plants was to replace steam and hydraulic drives on cranes, hoists, roll tables and other auxiliaries. By the beginning of the present century, the advantages of electric drive for all auxiliaries were well established and the changeover was proceeding rapidly. Even operators who continued to purchase engines for main power units used electric auxiliaries.

As it became necessary to analyze operating costs more closely it grew increasingly evident that the

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operating cost of large engine drives was usually excessive for the service rendered. This was not due so much to excessive steam consumption of the engines themselves as it was to the inherent disadvantages of the steam power system. Rolling mills are usually scattered over a considerable area. This

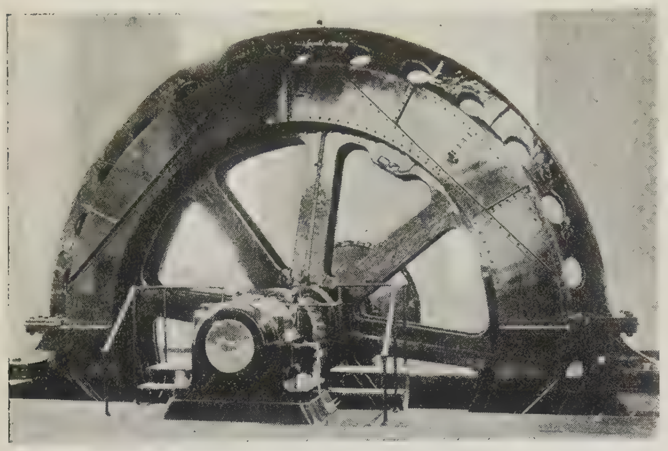


Fig. 1. Typical slow speed induction motor drive. Synchronous motors are now used for this application

made it necessary either to have a separate boiler plant for each mill or long steam lines to a central boiler plant. Where there were a number of reversing drives, either arrangement was unsatisfactory because of the enormous momentary demands for steam. Because of the standby and transmission losses, the engines seldom utilized more than 65 per cent of the total steam generated and usually the figure was much lower. Steam system maintenance costs were also excessive.

The successful and economical operation of electrically driven auxiliaries caused steel plant engineers to become interested in using electricity for main roll drive. Test data on existing engine drives were being compiled in such a way that they could be used in selecting motor drives for new mills.

The first installation of motors for main roll drive was made in 1905 at the Edgar Thomson Works of the Carnegie Steel Company, near Pittsburgh, Pa. This installation consisted of 2 1,500-horsepower 100/125-rpm 220-volt d-c motors driving a light rail mill. At about the same time the first electric reversing mill drive was purchased to drive a universal plate mill at the South Chicago plant of the U.S. Steel Corporation. This installation was followed in 1910 by a reversing blooming mill drive at the Algoma Steel Company, Sault Ste. Marie, Ontario. The Gary (Ind.) plant of the U.S. Steel Corporation, on which construction work was begun in 1906, was laid out for electric drive for both main rolls and auxiliaries, as far as was practicable with equipment then available. This was the first steel plant to be designed to use electric power for practically all operations. It is interesting to note that every one of the pioneer electrical installations mentioned above is still in service and operating at the original efficiency.

Power Generation and Distribution

By 1910 it became evident that steel plants eventually would be operated almost entirely by electric power and that suitable electric power systems would have to be installed. At that time the steam turbine and steam generating equipment were not highly developed, especially in small units of 5,000 kw or less, which was about the maximum capacity that steel makers were then willing to tie up in one unit.

Gas engines which could operate on available blast furnace gas could be had in capacities of 2,000 to 3,500 kw and would generate a kilowatthour on 15,000 to 18,000 Btu. A great many gas engine generating units were installed, a large part of which is still in use. The speed regulation of the older engines is poor, because of variations in the quality of the gas and on account of the slow speed (83 rpm). The variations in system frequency which occur as a result of poor engine regulation often have an undesirable effect on plant operations, so it was common practice to operate turbogenerators in parallel with gas engine units to give stability. Gas engines were improved and units as large as 6,000 kw installed, but the need for large generating units and the improvement of the steam turbine and boiler plants have made it desirable to use steam turbine units for power plant extensions.

In a modern steel plant, blast furnace gas is used to generate superheated steam at 250 to 300 pounds pressure. Steam generators are also equipped to burn coke breeze or coal. Part of this steam is utilized in steam turbocompressors to produce the air blast for the blast furnaces. The remaining steam is utilized in turbogenerators of 15,000 to 30,000 kw capacity. Waste heat from open hearth furnaces also provides a source of power which is being utilized to an increasing extent. A battery of 14 150-ton furnaces installed a few years ago was

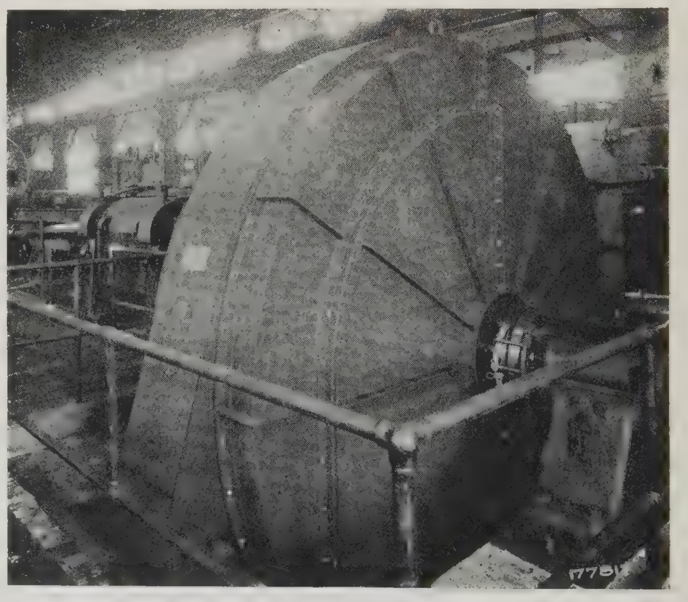
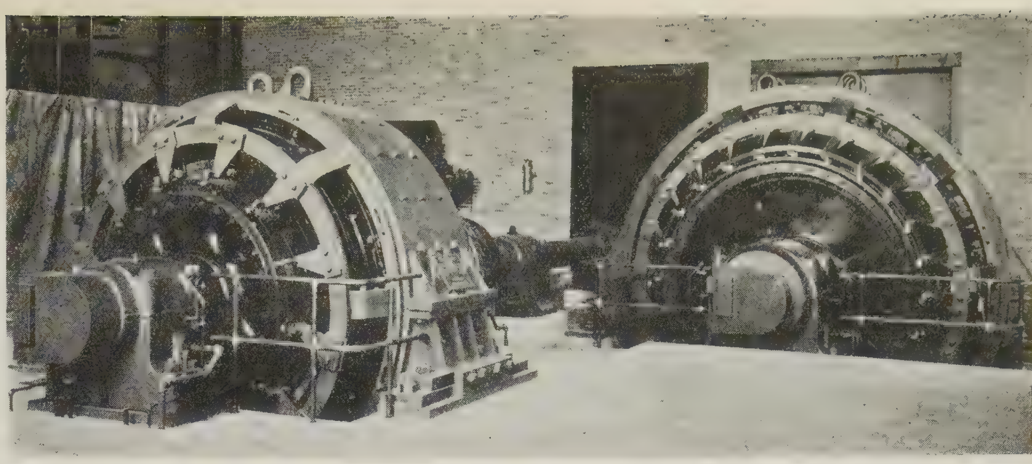


Fig. 2. A 1,800-horsepower 150-rpm 6,600-volt synchronous motor driving tube piercing mill. Loads are heavy and of such duration that flywheels are undesirable for load equalization

Fig. 3. 7,000 horsepower and 2,000 horsepower reversing motors operating in parallel. The 7,000 horsepower motor in the background drives the main horizontal rolls of a universal mill. The 2,000 horsepower motor drives a pair of vertical rolls in synchronism with the main rolls



equipped with waste heat boilers, 2 10,000 kw turbogenerators, and an evaporator to generate steam at moderate pressure for general mill use. Each 150 ton furnace produces an average of about 750 boiler horsepower. Under normal operating conditions it is possible to obtain from waste heat practically all the electric power required for a steel plant. Dry quenching of coke promises to provide another source of waste heat.

Steel plants necessarily occupy a great deal of space and points where power is used are seldom near to the place where it is convenient to install generating equipment. Present power requirements make it necessary to generate and distribute at 6,600 or 13,200 volts. The former voltage is practically standard for large motors. For small finishing plants operating on purchased power, 2,200 volts is satisfactory. Widely scattered plants operating under the same management are usually interconnected by transmission lines operating at 22 kv or 44 kv. One such 44 kv system has a total connected generating capacity of 120,000 kw. Thus, every large steel plant is confronted with the same problems of power generation and distribution as the utilities.

Electric Motor Well Suited for Main Drive

In the early stages of the electrification of the industry, the performance of the steam engine on main roll drives was the standard by which motor drive was judged. Mill design and rolling processes had been worked out to suit the characteristics of the engine. Except for reversing service, in which the speed was regulated manually, the reciprocating engine was essentially a constant speed power unit. Early rolling mills, except reversing type, therefore, were designed to operate at practically constant speed. It was then necessary to have a number of mills, each with a limited range of product. As experience was gained in applying motors, it became evident that by careful co-ordination of mill design and motor design to take advantage of the greater flexibility of the electric motor, mill performance could be improved. So, modern mills may use several types of electric drive in a single installation and a wide range of product can be rolled. In one recent instance, 7 old mills were replaced by a single mill with modern electric drive.

Recently great advances have been made in rolling mill processes. For example, all plate formerly was rolled in mills having not more than 2 independently driven stands of rolls and in most cases only a single stand. In such mills, plate can be rolled only in short lengths and coarse gauges. The modern mill has as many as 10 independently driven roll stands arranged in tandem and with finishing stands closely spaced. The total connected motor capacity is usually between 30,000 and 40,000 horsepower. Such mills, known as wide strip mills, may have rolls up to 100 inches long and can roll long plates in heavier gauges, or long coils of wide thin material known to the trade as strip.

Wide strip mills have been made possible through advances in mechanical design of mills and by the development of the adjustable speed d-c motor. The first 4 roll stands, which are spaced so the steel is in only one stand at a time, are usually driven by synchronous motors or induction motors of about 2,500 horsepower rating. The finishing stands are closely spaced and are each driven by a 600-volt d-c adjustable speed motor with a 2 to 1 speed range by field control. These motors vary in capacity from 2,000 horsepower to 3,500 horsepower in existing installations.

Likewise, the methods of producing sheet and tinplate have undergone a tremendous change. Formerly all sheet and tinplate was produced by a slow and laborious process. Small bars were heated, rolled to light plate, reheated in packs of 2 or more and the packs rolled, doubled, reheated and rerolled as often as was necessary to obtain the desired gauge. The modern method of rolling such material is to start with a coil of strip weighing several tons and cold roll it directly to the desired gauge in one operation. Mills for this process may be either multi-stand tandem mills or single stand reversing mills. D-c adjustable speed motors are used for either type of mill with special control equipment to keep the steel under tension during rolling.

And so, through the entire list of finished steel products, it will be found that present day processes all depend heavily on drive characteristics which can be obtained only with the electric motor. A review of the various types of motors and their application to main roll drives will serve to illustrate this point.

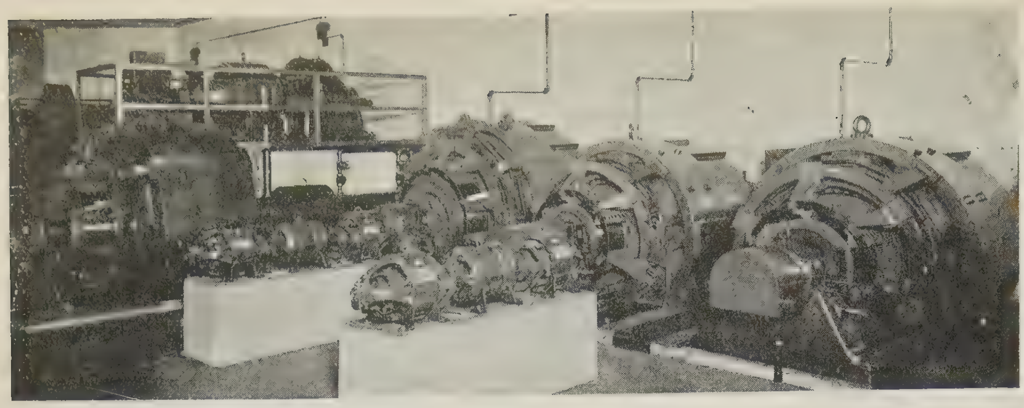


Fig. 4. Typical installation of d-c adjustable speed motors for high speed tandem mill drive

Induction Motors

The induction motor has been widely used in the past for 2 main types of drives: (1) constant speed drives which were subjected to heavy peak loads of short duration, and which required high starting torques; and (2) constant speed drives for continuous type mills in which a number of stands were driven from a common shaft. For the first type of drive, wound rotor motors and flywheels and fixed or adjustable slip resistance are used. This arrangement was especially popular when power systems were small and it was necessary to protect generating equipment against short, heavy peaks. Induction motors up to 7,000 horsepower capacity have been used for this type of drive. Changes in mill design and increase in power system capacity have greatly reduced the demand for induction motor drives with flywheels for equalizing load peaks. Induction motors were used for the second type of drive largely because suitable synchronous motors were not available. A typical slow speed induction motor drive is illustrated in figure 1.

A number of systems have been developed for speed regulation of wound rotor induction motors, and 145 equipments ranging in capacity up to 7,500 horsepower have been installed. Due to changes in mill design and the demand for maximum simplicity of electrical equipment there is little application for a-c adjustable speed motors.

Synchronous Motors

Improvement in synchronous motor design and increase in capacity of power systems now make it possible to use synchronous drive for many constant speed applications for which induction motors were used previously. The synchronous motor is the ideal drive for certain types of multi-stand mills in which one motor drives a number of roll stands and the load is steady. Paradoxically, the synchronous motor may also be superior to other types for operations which impose heavy peak loads. In a seamless tube plant, for example, a large piercing mill requires 10 to 20 seconds to pierce a billet and the motor load will be several thousand horsepower. In the interval between billets the load is negligible. Because of the relatively long load period, an excessively heavy flywheel would be required to equalize such a load if induction motor drive were used and a definite period would have to be allowed between operations to permit recovery to no-load speed. An installation of this type is shown in figure 2. Between the comparatively steady load and the load which consists of a succession of long, heavy peaks there also are a number of constant speed loads for which the synchronous motor is suitable.

Small and medium capacity synchronous motors are started at full voltage. Larger motors are usually wound with 6 primary leads so that a starting reactor can be connected permanently in the neutral. This reactor is short-circuited by a 2 pole circuit breaker as the motor approaches synchronous speed. By proper design of the rotor cage winding, the starting torque can be made to suit a wide range of conditions. Synchronous motors up to 9,000 horsepower are in successful operation.

D-C Reversing Equipments

Reversing motors are used principally to drive heavy primary reduction mills such as blooming and slabbing mills which reduce the original ingots to sections which can be used in finishing mills. Reversing stands are used also for making roughing passes in rail, structural, and plate mills. Over 100 reversing equipments varying in continuous capacity from 500 horsepower to 12,500 horsepower have been built in the United States. These drives usually consist of a specially designed reversing motor having a speed range of at least 2 to 1 by field control; a motor generator consisting of one or more variable voltage generators, a wound rotor induction motor and a flywheel; a slip regulator to equalize the input to the motor generator; and a variable voltage control. In special cases a synchronous motor-generator can be used. The speed and direction of rotation are controlled by a small foot master switch. A special form of reversing drive in which 2 motors drive separate pairs of rolls in the same mill housing is shown in figure 3.

Reversing drives are usually direct connected to the mill rolls, so the motors are designed for slow speeds and heavy torques. The most powerful equipment built to date has 2 5,000-horsepower, 40/80-rpm motors, one connected to each of the main horizontal rolls of the mill, and a third motor of 2,500 horsepower capacity for driving a pair of vertical edging rolls. The combined maximum

torque capacity of the 5,000 horsepower main motors is 3,950,000 pound-feet. The use of the twin-motor arrangement makes it possible to apply extremely high capacity slow speed drives to a single pair of rolls.

D-C Adjustable Speed Motors

The tendency to design modern finishing mills for a wide range of product frequently makes it necessary to drive each stand of rolls with an individual adjustable speed motor. Mill stands usually are arranged in tandem on close centers so that it is necessary for the mill operator to have close control of the speed of every motor in the roll train. The d-c motor is peculiarly adapted to this class of service. (A typical installation is shown in figure 4.) The d-c motor is indispensable for cold roll mills, in which both the speed of the mill and the tension on the metal must be regulated closely.

A brief explanation of the operation of a single stand reversing cold roll mill will serve to show the flexibility of the d-c motor and its control. Such a mill consists of a roll stand with 2 working rolls and a driving motor and 2 motor driven reels; one on either side of the roll stand. A long coil of hot rolled strip weighing several thousand pounds is placed in the reel on the entry side of the mill and the end of the strip is threaded through the rolls at slow speed and into the jaws of the reel on the delivery side. Electrical adjustments are made which place the strip under tension on both sides of the mill and the mill and reels are brought up to speed by variable voltage control. Due to the decreasing diameter of the coil on the entry side, the speed of the reel must increase as rolling progresses. The motor acts as a generator while maintaining the desired back tension. On the delivery side, the diameter of the coil increases so the delivery reel drive, acting as a motor, must continually decrease its speed while maintaining the strip under constant tension. Successive passes are made in opposite directions so the functions of the reel drives are reversed for each pass.

A Stroboscopic Power Angle Recorder

An automatic stroboscopic power angle recorder developed to study directly the transient performance of synchronous machines during load disturbances is described in this paper. A portion of the machine under observation is illuminated by stroboscopic light, and its oscillations are recorded directly by a moving-film camera. The operation of the device is made automatic by connecting a suitable relay in its circuit. A typical installation on a hydroelectric generator is described.

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The automatic stroboscopic power-angle recorder described in this paper, an instrument that might be called the "strobograph," makes possible the direct recording of the power angle of synchronous machines—a measurement otherwise very difficult to obtain especially during disturbances. The present strobograph is an improvement of an earlier model described in Electrical Engineering, May 1931, pages 327–9.

The electromagnetic oscillograph has been used for the study of transient conditions in power networks, and has produced commendable results. Several types of oscillographic instruments capable of great flexibility and usefulness have been developed, particularly for obtaining records showing what happens during disturbances. A serious limitation of the oscillograph, however, is that it cannot measure the power angle directly in the way that it records voltage or current, since the power angle cannot be measured electrically at the terminals. The power angle is one of the most important variables to measure, since stability is a function of this angle. Auxiliary apparatus such as a pilot a-c generator (having the same number of poles as the machine under test and rigidly connected to it) or a special commutator can be used in conjunction with the oscillograph to record the power angle, but these methods seldom are employed because they are difficult to arrange, especially upon large machines.

A stroboscope permits the direct measurement of the power angle. Stroboscopic light, flashed in constant phase relationship with the stator voltage, shows the field poles in a stationary position in space when the machine is running in synchronism at constant load. As the load changes, the poles can be seen to move to their new equilibrium position and oscillate about it. The oscillation is over in a few

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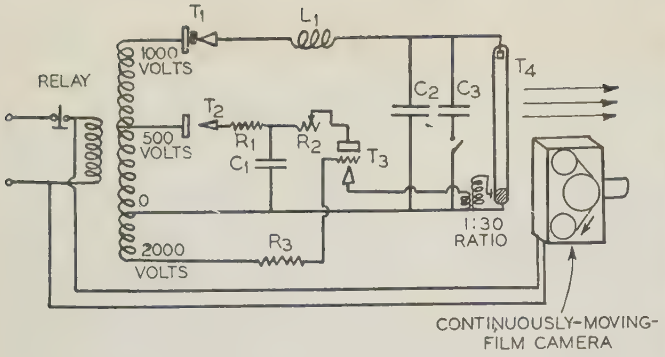


Fig. 1. Wiring diagram of a stroboscope for producing one flash of light each cycle in accurate phase relationship with the voltage

R_1 20,000 ohms
R_2 100 ohms
R_3 20,000 ohms
T_1 Type 866 rectifier tube
T_2 Type 280 rectifier tube
T_4 Mercury arc stroboscope tube
L_1 1 henry or 300 ohms resistance
C_1 0.25 microfarad
C_2 1 microfarad
C_3 3 microfarads
T_3 Type FG-17 grid-controlled mercury-vapor tube

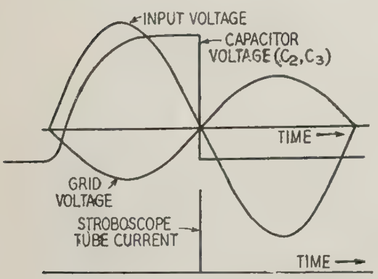


Fig. 2. Voltage and current variations in circuit of figure 1

seconds—in fact, so quickly that it is impossible to measure with the eye the angle time curve—but with a camera a series of readings may be exposed on the film. The stroboscope for this purpose must produce light having several properties which will be discussed in detail later.

This paper describes a method of measuring the power angle during disturbances by photographing the field structure with stroboscopic light. An application of the method was made in the Bellows Falls, Vt., plant of the New England Power Association during the summer of 1933, and some of the results are shown.

Stroboscopic Method of Measuring Power Angle

Speed and angle measurement with stroboscopic light have long been in use in the operation of synchronous machines, and the principles involved are well understood by engineers and operators of power systems. The method is not in general use at the present time because there has been a lack of a suitable convenient high-power source of stroboscopic light. The stroboscopes described in this paper overcome this objection. The method was developed in the electrical engineering department at the Massachusetts Institute of Technology in order to measure the transient performance of synchronous machines during load disturbances.

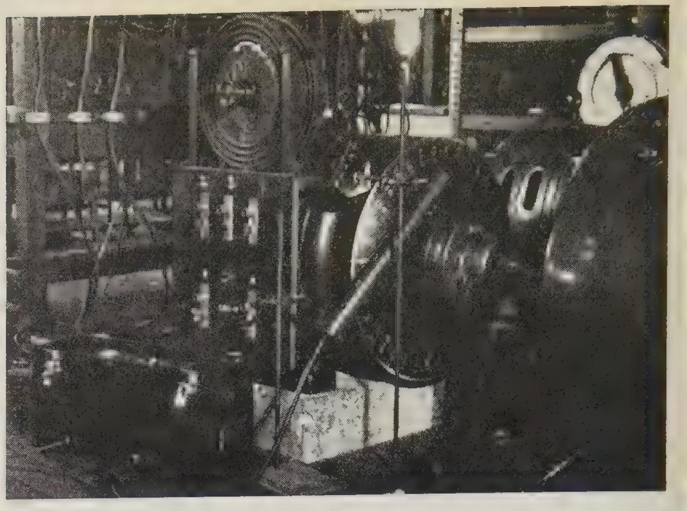


Fig. 3. A stroboscope in the laboratory of the Massachusetts Institute of Technology for measuring the angular displacement of a synchronous motor

The requirements of a suitable stroboscope for making photographic records of power angle transients are:

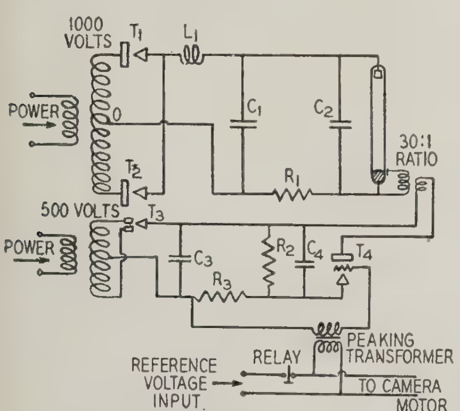
1. An accurate *phase relationship* between the time of flash and the terminal voltage.
2. A brief flash of light (less than 10^{-5} second). A short flash is necessary in order to produce a clear unblurred image of the moving scale or pointer.
3. A great instantaneous intensity of illumination. This is important when pictures are needed for obtaining records.

One circuit arrangement that is very satisfactory is shown in figure 1. A short flash of light is produced each cycle from the mercury arc tube at a time corresponding approximately to the time when the supply voltage is zero. The magnitude of the input voltage can be varied without any appreciable change in phase shift between the flashes and the voltage. Experiment shows that the error in angle measurement is less than $^1/_2$ an electrical degree for a voltage change from -10 per cent to $+10$ per cent. Limitations to the allowable variations of voltage depend primarily upon the filaments of the rectifier tubes, T_1 and T_2 and the vapor tube T_3. Should the voltage drop too low, the electron emission becomes insufficient and the oxide surfaces of the cathodes are damaged. The filaments, however, have appreciable thermal time constants that permit them to operate for brief intervals without difficulty following a sudden drop of voltage. Where violent voltage variations are expected, the filaments should be heated separately from an auxiliary circuit the voltage of which is known to be reasonably constant.

A flash of light from the mercury arc stroboscope lamp results when a capacitor that is connected directly across it discharges violently through the tube. For the conditions shown in figure 1 the capacitor is 4 microfarads and it is charged to about 1,200 volts for each flash. In normal operation the mercury tube does not break down with this voltage across it until a high suddenly applied potential is impressed on the starting band at the junction of the mercury and glass. A cathode spot quickly forms

on the edge of the liquid mercury when the high voltage surge arrives, and it furnishes ample electron emission to discharge the capacitor at a rapid rate. Naturally the current through the tube reaches a large value, since there is very little impedance in the discharge path. This sudden pulse of current as it passes through the mercury tube excites the mercury vapor and causes it to produce the brief intense flash of light that is used for stroboscopic observation and for instantaneous photography.

The high voltage pulse for starting the mercury tube is obtained in this circuit from the secondary of a step-up transformer when a small capacitor ($^1/_4$-microfarad charged to about 600 volts) is discharged into the primary. The vapor tube T_3 n figure 1 acts as a switch to connect the small capacitor to the primary of the external-grid exciting transformer at a time when the grid of T_3 is at about zero potential. Before this time the grid voltage on tube T_3 has been negative, which prevents it from conducting during the time that the small capacitor is being charged from the power transformer through the rectifier tube T_2. The large capacitor (C_2, C_3) across the mercury lamp is charged at the same time through the rectifier T_1. The a-c grid voltage has



C_1 10 microfarads
C_2 4 Microfarads
C_3 10 microfarads
C_4 0.25 microfarad
R_1 2,000 ohms
R_2 100,000 ohms
R_3 10,000 ohms
L_1 5 henrys
T_1,T_2 Type 866 rectifier tubes
T_3 Type 83 rectifier tube
T_4 Type FG-17 grid-controlled mercury-vapor tube

Fig. 4. Wiring diagram of a stroboscope for producing one flash of light each cycle

The circuit for tripping the light is not required to supply power to the stroboscope tube, as in the circuit of figure 1

Fig. 5. Looking up in wheel pit at Bellows Falls (Vt.) plant showing location of platform supporting stroboscope and camera

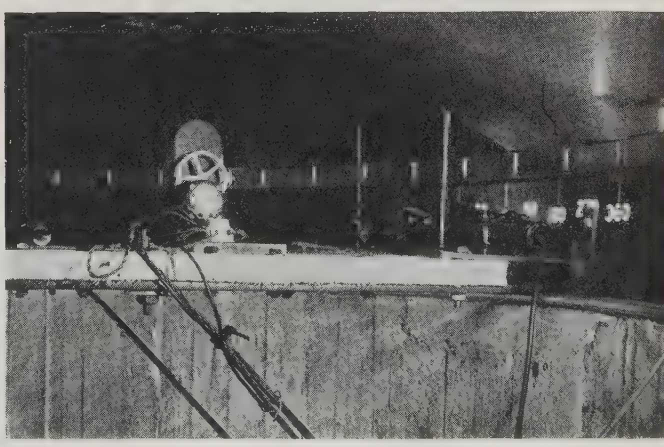
a value of several hundred volts so that the starting of conduction in tube T_3 will be nearly independent of the magnitude of the grid voltage or the temperature of the tube, this conduction starting when the grid voltage swings from a negative to a positive value. During the half-cycle that the grid of tube T_3 is positive the plate voltage on both rectifier tubes is negative, and so no current flows through them. The current to the grid of T_3 is limited by a resistor. Various voltage and current relations in the circuit are shown in figure 2.

Operation of the stroboscope is made automatic by connecting a relay (tripped by line or neutral current) in series with the primary of the power transformer, as shown in figure 1. The stroboscope starts to flash within one cycle after the transformer is energized and will run until disconnected, for instance by a definite-time relay arranged to open the circuit in about 10 seconds, which is long enough to cover the duration of most power angle transients. In this automatic use, the tube filaments need to be heated continuously so that they will be ready to operate immediately.

For intermittent duty such as the 10 second service just mentioned, the power to operate the stroboscope is between 100 and 200 watts, depending upon the exact arrangement used. Continuous operation will overheat the mercury lamp and it will begin to miss and "stutter" unless cooled or unless the power into the lamp is reduced by lowering the voltage or capacitance. A switch is shown in figure 1 for disconnecting capacitor C_3 from the circuit for continuous operation. The useful life of the mercury tubes depends upon their treatment in the circuit; like all other electronic devices, the harder they are worked the shorter is their life. In automatic service the stroboscope lamps should be tested occasionally and replaced after 10 or 20 operations. The lamps become dark on the inside after use, which reduces light output. At the Bellows Falls application it was necessary to wipe the dust off the tube and reflector at least once a week.

A second type of stroboscope, the circuit of which is shown as figure 4, has one advantage over that of figure 1, in that it requires less power from the reference voltage circuit. Power to operate the vapor tube control circuit and the mercury arc lamp for this circuit is obtained from a source of power that

Fig. 6 (right). View showing reference marks (one for each pole) on inside rim of rotor, stationary scale, stroboscope, and camera



may be independent of the a-c source used as a reference voltage. A peaking transformer is connected in the vapor tube grid circuit to give a peaked wave form on the secondary and thereby cause the tube to be "tripped" suddenly at the same angle, even if the magnitude of the reference voltage may vary over a considerable range.

Values of circuit constants that have been used in the laboratory are indicated on the circuit diagrams, figures 1 and 4. Because of the fact that the mercury stroboscope lamp is operative over a large range of voltage, the circuits are not critical to changes of the circuit constants.

Power Angle Recorder at Bellows Falls

During the summer of 1933 a stroboscope of the type shown in figure 4 was installed in the wheel pit of generator 1 at the Bellows Falls plant of the New England Power Association. The stroboscope and the camera were held underneath the rotor by a platform fastened to the concrete walls. One white reference mark was accurately located by means of a scriber on the inside rim of the rotor for each of the 48 poles of the machine. Below this rim with the index marks was placed a stationary scale reading directly in electrical degrees. Photographs of this installation are reproduced in figures 5 and 6. The mercury-arc stroboscope tube is in a protecting fiber tube and is located just below the scale (figure 6).

The camera for recording the angle was a rebuilt 16-millimeter hand-cranked motion-picture camera in which the intermittent motion had been removed so that the film moved continuously. A $^1/_{20}$ horsepower synchronous motor was geared to the drive and arranged to pull the film past the gate at the rate of exactly 60 frames per second. The removal of the intermittent motion greatly reduced the torque required to drive the camera. With this arrangement the film came up to speed within less than $^1/_{10}$ second after the motor was connected.

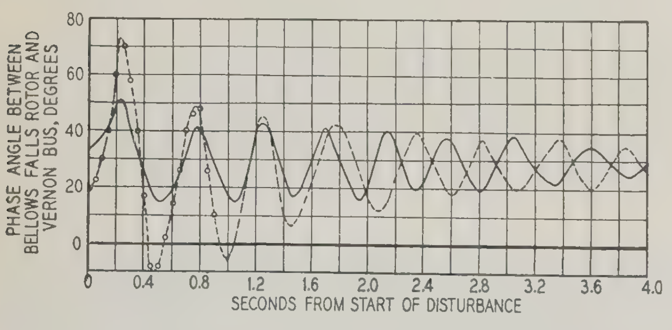


Fig. 7. Two angle-time curves recorded automatically at Bellows Falls during the 1933 lightning season

—Single phase fault --- 2 phase fault

During the 10 seconds that the definite-time relay permits the camera to run, about 14 feet of film is exposed. Thus with 100 foot supply on rolls of film, about 7 disturbances are recorded without reloading the camera. Two typical records obtained from films taken at the Bellows Falls plant are plotted in figure 7.

D-C Braking of Induction Motors

The rapid deceleration of induction motors from relatively high speeds to standstill by the application of constant potential to the terminals is considered in this paper. Applications in which d-c braking of induction motors is desirable are mentioned, and the fundamental principles involved in this method of braking are considered. The characteristics of the speed-torque curve are derived from these principles. The practical application of d-c braking is demonstrated by the results of extensive tests, and a simple means of calculating the approximate values of current and wattage necessary for braking is included.

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THESE days of high speeds in transportation and in industrial processes have given rise to new problems incident to acceleration to and deceleration from these increased speeds. Whereas acceleration frequently comes in for a major share of the consideration in connection with high speed problems, this paper deals entirely with deceleration—or more specifically with the deceleration of loads powered by a-c induction motors.

The evolution of that portion of the steel industry having to do with the production of steel strips and sheets has brought into existence the modern so-called continuous strip mill. In this mill, all the steps in the process of reducing a slab to strips or sheets are made part of a continuous and progressive sequence of operation, and entirely new problems of deceleration are presented.

The increase in mill speeds when handling hot steel shapes from 300 feet per minute up to actual present operations at 1,600 feet per minute and

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higher, requires the complete control of the entire mill with much greater facility than was previously occasioned. Particularly is this true of the so-called finishing end of a mill where the higher linear speeds are attained, and where the material already has sufficient value as represented by its successive processing as to require the most complete flexibility of handling means in order to dispatch the finished product successfully.

The application of a constant potential to the terminals of very large induction motors has not been unknown for accomplishing an economical and practicable braking effect. It remained, however,

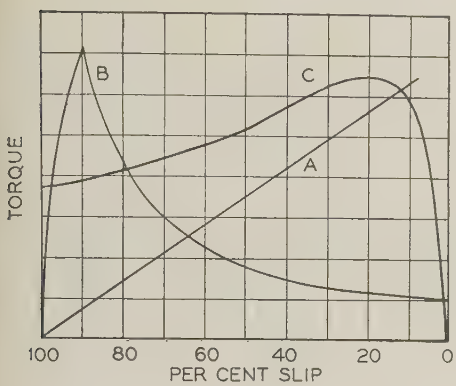


Fig. 1. Characteristic torque curves showing: original and present conception of d-c braking (curves A and B, respectively) and standard induction motor torque curve (curve C)

for the necessities arising from the operation of modern continuous mills to bring this old principle of d-c braking of induction motors—both singly and in groups—into further prominence.

It was the problem of successfully handling the necessary deceleration of strip steel on the conveying rollers and coilers of continuous mills, which in turn

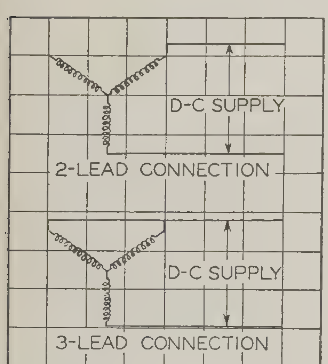


Fig. 2. Schematic wiring diagram showing 2 methods of applying direct current to 3-phase stator terminals

were powered by individual induction motors, that prompted further investigation of d-c braking for such a purpose.

As it has been proved many times in the past, some well-known phenomenon when brought into the limelight and investigated, proves to have somewhat different characteristics and behavior than generally ascribed to it. So it is with d-c braking of induction motors.

It has been generally considered that the characteristic d-c braking curve of an induction motor was from a maximum at top speed down to zero at standstill, as illustrated by figure 1, curve A. While this is a possible curve for a very high resistance wound rotor induction motor, the most representative curve of the family for induction motors or more particularly squirrel cage motors, is that shown in figure 1,

A—Rotor having normal resistance
B—Rotor having twice normal resistance
C—Rotor having 4 times normal resistance

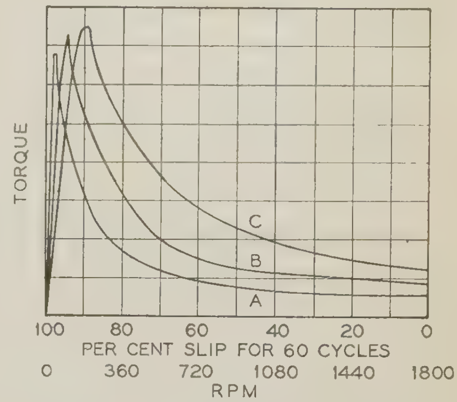


Fig. 3. Characteristic torque curve of 4-pole squirrel-cage motor during d-c braking. Three types of rotors, normal torque (A), semi-high torque (B), high torque (C)

curve B. It may be of interest at this point to observe that the general shape of the d-c braking curve is the opposite of the typical squirrel cage speed curve which might be illustrated by curve C, figure 1.

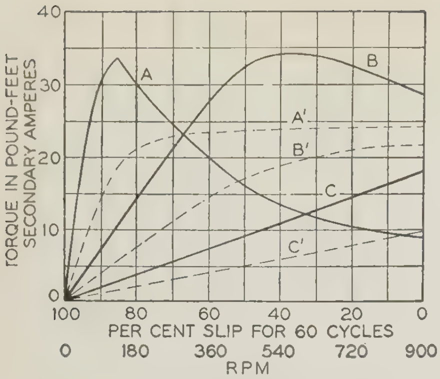
Throughout this paper curves will be presented in which d-c braking torque in pound-feet is plotted against speed in revolutions per minute. In every case the speed scale will be limited to that speed which would be attained if the motor were to be connected to a 60 cycle supply since that frequency represents the present limits of commercial frequency.

Principles Involved in D-C Braking

It would be well to review just how this braking effect is secured. An induction motor which is rotating at synchronous speed less a small slip and driving a load, upon removal of the a-c supply tends to continue rotating at its original speed, except as the friction and windage of the connected load, plus that of its own rotor, retard it.

D-c braking may be accomplished by applying the potential to either 2 or 3 terminals of a 3-phase induction motor, as illustrated in figure 2. This direct current produces a number of fixed poles of constant polarity and intensity in the stator or primary, equal in number to the poles for which the machine is wound. In this field the rotor in motion resembles a short-circuited armature of as many parallel circuits as there are rotor bars, the short-circuiting rings forming the end connections. There is produced at each rotor bar an alternating potential giving rise to a circulating current such as to oppose rotation.

To carry this review a step farther, consideration will be given to the speed-torque curves of d-c braking on a 4-pole squirrel-cage induction motor when disconnected from a 60 cycle supply with,



Torque curves solid lines; secondary current curves dotted lines
Curves A, A′ without external resistance
Curves B, B′ with 5 ohms external resistance
Curves C, C′ with 20 ohms external resistance

Fig. 4. Characteristic curves of torque and rotor current for an 8-pole wound-rotor induction motor during d-c braking

successively, rotors having characteristics incident to producing normal torque and normal slip, then semi-high torque, and full high torque rotors; or in other words, rotors all having the same reactance as determined by the shape and positions of the slots and end rings, but differing in resistance value as determined by the material in the bars and rings. These curves are shown in figure 3, where curve *A* is that for a normal resistance rotor, curve *B* is that for a rotor having twice normal resistance, and curve *C* that for a rotor having 4 times normal resistance. The curves are all taken with the same value of d-c amperes flowing continuously between stator terminals.

They serve to illustrate several important details of d-c braking. At first consideration it seems illogical that the maximum braking effort should come at other than maximum speed where maximum voltage is produced. However, it must be borne in mind that at any speed with direct current impressed on the stator terminals, the voltage produced in the rotor has an instantaneous frequency indicated by the well-known formula

$$f = \frac{p}{2} \times \frac{\text{rpm}}{60} \qquad (1)$$

where p is the number of poles.

Thus, at the instant a 4 pole motor (1,800 rpm) should be disconnected from a 60 cycle line and have direct current impressed on its primary terminals, the frequency in the secondary would be approximately 60 cycles, decreasing directly with the speed to zero frequency at standstill. During deceleration the secondary voltage is a direct function of the speed, as would be expected and as verified by oscillograph charts taken on a wound rotor motor.

The secondary current will then decrease with the speed at a rate determined by the proportion between the resistance and reactance comprising the rotor impedance. This is verified by an oscillographic study of the secondary current in a wound rotor motor of known constants during d-c braking.

The increasing torque, then, in the face of a decreasing current be explained by the phase relation between the secondary voltage and current. As the rotor comes down in speed, the power factor of the secondary approaches unity, bringing the peak current into the most effective position to produce maximum braking effect.

This is illustrated by the curves in figure 4 representing the braking speed-torque curves and the accompanying secondary curves for an 8-pole wound-rotor induction motor operated from a 60 cycle supply. Curves *A* and *A′* are torque and current

Torque curves solid lines; secondary current curves dotted lines
Curves A, A′ without external resistance
Curves B, B′ with 5 ohms external resistance
Curves C, C′ with 20 ohms external resistance

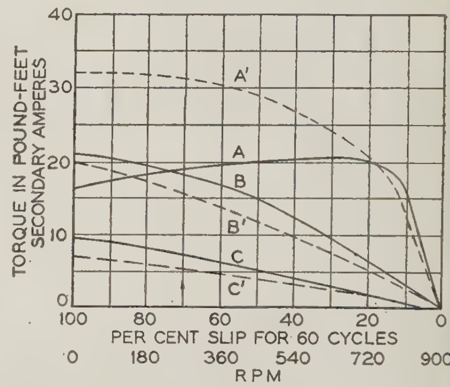


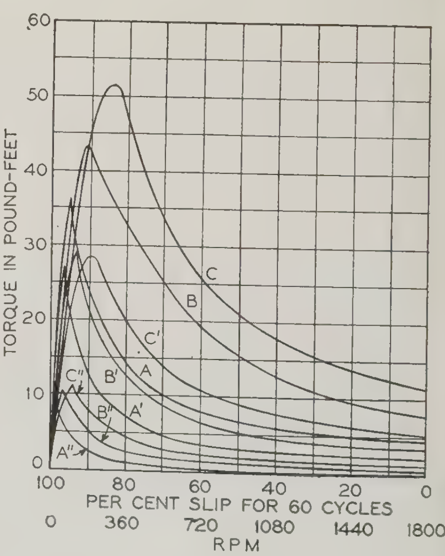
Fig. 5. Characteristic curves of torque and rotor current versus slip for an 8-pole wound-rotor induction motor. Curves with no external resistance and with 2 values of external resistance in the rotor circuit

respectively taken without external resistance in the rotor circuit. Curves *B* and *B′* are taken with an external resistance of 5 ohms, while curves *C* and *C′* are taken with 20 ohms external resistance. These are all taken with the same d-c excitation.

It is simply an item of interest to note the similarity of character of the torque and current curves

Fig. 6. Four-pole squirrel-cage motor torque versus slip curves for d-c braking illustrating variation of torque for changes of rotor resistance up to 4:1 and changes in d-c amperes supplied to the stator up to 3:1

See text for meaning of curves



for d-c braking in figure 4, with their corresponding speed-torque curves and current curves taken on the same motor with the same external resistances, and as powered from a 60 cycle source of supply, all as shown in figure 5. Aside from their similarity and the fact that secondary resistance and reactance have similar effects on both a-c motor and d-c

braking torque curves because of like rotor frequency in both cases, there is no comparison of area under the curves applicable to the problem of stopping. The a-c motor when plug-stopped by alternating current has not the curve shown in figure 5, but an extension of these curves for values of slip from 100 per cent to 200 per cent, and, of course, the d-c excitation of the stator cannot produce rotation for acceleration.

It is also obvious that the entire speed-torque curve for a given motor—i. e., stator winding and rotor winding of given design—can be raised and lowered along the Y axis by adjusting the d-c potential applied to the stator terminals. This relation is one of the second power representing the product of volts and amperes. Thus, a given motor producing say 10 pound-feet braking torque at a speed of 600 rpm with 5 amperes d-c excitation, should produce 40 pound-feet at the same speed with 10 amperes direct current.

This change in torque is, of course, subject to the limitation of saturation of the core, but for the range of stopping time apt to be required in stopping induction motors, this relation safely can be assumed to apply.

Illustration of These Principles

Figures 6, 7, and 8 serve to illustrate the foregoing statements with regard to d-c braking characteristics for 4, 8, and 12 pole motors, respectively. Figure 6 shows in curves A, B, and C, the braking curve of rotors with normal resistance, twice normal resistance, and 4 times normal resistance, respectively, all taken with the same value of d-c excitation on the stator terminals of a 4 pole motor. Curves A', B', and C' are for the same rotors but with a d-c excitation value approximately 67 per cent of that for the curves A, B, and C. Curves A'', B'', and C'' are for the same rotors but with a d-c excitation value approximately 33 per cent of that for curves A, B, C.

With particular reference to figure 6 where there are shown 3 separate sets of curves, each with different current values, it will be noted that the maximum torque point occurs at a higher speed at each successive increase in d-c excitation. This is to be expected due to the effect of saturation of the leakage paths in the rotor and the increased rotor resistance incident to the increase in heating occasioned by the securing of such curves.

Curves A, B, and C in figure 7, as in figure 6, illustrate 3 different rotor resistances with a fixed value of d-c braking current in an 8 pole motor, with curves A', B', and C' representative of the similar results but with approximately 50 per cent of the d-c excitation value.

In the same way figure 8 illustrates exactly the same results for 3 rotor resistances and 2 values of d-c excitation, curves A', B' and, C' being taken with approximately 50 per cent of the d-c value used for securing curves A, B, and C.

All of the foregoing curves in figures 6, 7, and 8 may be secured by driving an induction motor through a dynamometer over a wide range of speed and measuring torque at incremental steps over this entire range, repeating the process for different values of d-c excitation.

Characteristics of D-C Braking

With the evidence thus far disclosed, certain general characteristics are fairly well established:

1. It is recognized that the speed at which the maximum torque will occur may be adjusted by a change in secondary resistance.
2. It is recognized that the slope of the braking curve from top speed to the maximum torque point can further be shaped by the inherent secondary reactance.
3. It is recognized that the amount of effectiveness of d-c braking secured will be a direct function of the d-c wattage input or the second power of the d-c amperes.
4. It is recognized that the shape of the speed-torque curve for d-c braking on squirrel cage motors is approximately correct for taking advantage of the change in the coefficient of friction between metal and a rotating conveying surface, such as between steel strip and a conveyor table roller.

With regard to the point 4 above, it has been frequently observed that plug reversing a group of induction motors, as on steel mill runout tables, for stopping them with material on the table may result in slippage of the material on the table because there is more braking torque available than the coefficient of friction and weight of material on the table can absorb. Consequently, slippage ensues. This may

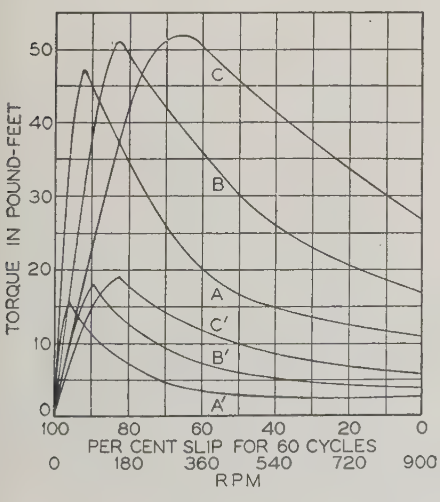
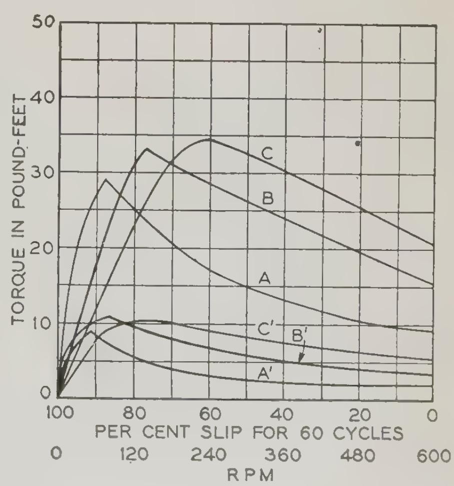


Fig. 7. Eight-pole squirrel-cage motor torque versus slip curves for d-c braking illustrating variation of torque for changes of rotor resistance up to 4:1 and changes in d-c amperes supplied to the stator up to 2:1

See text for meaning of curves

Fig. 8. Twelve-pole squirrel-cage motor characteristic torque versus slip curves for d-c braking illustrating variation of torque for changes in rotor resistance up to 4:1 and changes in d-c amperes supplied to the stator up to 2:1

See text for meaning of curves



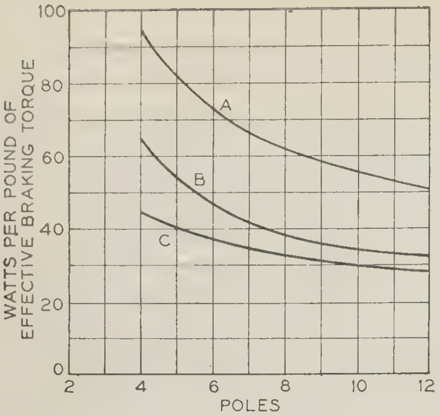


Fig. 9. Curves of power required for d-c braking of induction motors

A—Rotor having normal resistance

B—Rotor having twice normal resistance

C—Rotor having 4 times normal resistance

be compensated for in d-c braking, partially in the shape of the curve and then completely by adjusting the d-c excitation.

Tests Demonstrating Practical Application

For the purpose of making practical application of d-c braking to a squirrel-cage motor having a connected load of known inertia, a series of very enlightening tests on motors of the same physical frame size, but wound for 4, 8, and 12 poles, each with 3 different rotor resistances, have been conducted.

As conducted, a load of known moment of inertia (WR^2) was applied directly to the shaft of each motor, so that there was no added friction incident to extra bearings for the external load but only the windage of the flywheel, which was practically negligible. Data on starting, plug-stopping, and d-c braking of these motors with simultaneous readings of time, wattage, and current, together with the separately secured design and test data, are given in table I.

By way of further explanation, it should be pointed out that the value of average effective torque taken in each case, represents not a figure based upon the area under the speed-torque curve, but a value determined by formula from the known inertia and measured time as follows:

$$T = \frac{WR^2 \times \text{rpm}}{308 \times t} \quad (2)$$

These test results may well be approached from the standpoint of their practical value. First, the economy of d-c braking seems impressive. In so far as power input is concerned, it is apparent that the watts per pound-foot expended in a-c plugging in the most optimistic case is 3 times that for d-c braking, as in the case of the multi-pole machine, and may be very much more in the case of machines with fewer poles and different rotors, as a ratio of more than 6:1 is evident on the 4-pole 1,800-rpm motor with a full high torque rotor.

Figures 9 and 10 are compiled from the data in table I together with a vast amount of additional data and are meant to be representative of average figures of wattage per pound-foot torque for d-c braking and plugging, respectively. Observing these curves it becomes apparent that the ratio of power saving incident to the use of d-c braking over plugging may vary from 4:1 with a normal torque rotor to 6:1 with a semi-high torque rotor, or 7:1 with a full high torque rotor in a 4 pole motor.

At the same time, however, it should be noted that the average total loss expended within the motor for any number of poles or any resistance rotor is approximately the same, and the ratio for a-c plugging to d-c braking is about 2.25 1. In other words, the economy of d-c braking as regards power supplied to the motors may be from 3:1 up to 6:1 over plugging, depending upon rotor character-

Table I—Data Obtained From Tests. Comparison of Starting, Plugging, and Dynamic Braking

Rotor	Operation	Time in Seconds	Watts-Seconds Input	Pound-feet Effective Torque	Watts per Pound-foot of Effective Torque	Pound-feet A-C Starting Torque	Watt-Seconds Load Kinetic Energy	Watt-Seconds Loss in Motor	60 Cycle Speed, Rpm
A	Start	7.6	113,420	24.3	620	30.0	23,600	89,820	1,800
A	Plug	4.4	73,800	42.0	400	30.0	23,600	97,400	1,800
A	D-c brake	4.6	20,000	41.2	106	30.0	23,600	43,700	1,800
B	Start	7.0	74.800	26.3	406	44.3	23,600	51,200	1,800
B	Plug	3.2	64,000	57.6	346	44.3	23,600	87,600	1,800
B	D-c brake	3.7	12,000	49.7	65	44.3	23,600	35,600	1,800
C	Start	8.0	61,000	23.0	330	47.8	23,600	37,400	1,800
C	Plug	3.2	53,000	57.6	288	47.8	23,600	76,600	1,800
C	D-c brake	3.1	8,350	59.5	45	47.8	23,600	31,950	1,800
A	Start	4.0	21,750	23.0	236	15.2	5,900	15,850	900
A	Plug	3.8	20,000	24.2	218	15.2	5,900	25,900	900
A	D-c brake	3.4	6,030	27.0	66	15.2	5,900	11,930	900
B	Start	4.8	16,900	19.2	184	22.2	5,900	11,000	900
B	Plug	3.0	15,000	30.8	163	22.2	5,900	20,900	900
B	D-c brake	2.8	2,960	32.8	33	22.2	5,900	8,860	900
C	Start	7.4	16,200	12.5	176	26.1	5,900	10,300	900
C	Plug	2.8	18,000	32.8	195	26.1	5,900	23,900	900
C	D-c brake	2.9	3,060	31.7	33	26.1	5,900	8,960	900
A	Start	6.0	10,500	10.2	172	8.8	2,620	7,980	600
A	Plug	4.2	11,640	14.6	190	8.8	2,620	14,260	600
A	D-c brake	4.2	3,150	14.6	51	8.8	2,620	5,770	600
B	Start	6.0	6,200	10.2	101	13.2	2,620	3,580	600
B	Plug	3.0	6,000	20.4	98	13.2	2,620	8,620	600
B	D-c brake	3.4	2,020	18.1	33	13.2	2,620	4,640	600
C	Start	7.0	7,540	8.8	123	15.7	2,620	4,920	600
C	Plug	2.8	7,000	22.0	114	15.7	2,620	9,620	600
C	D-c brake	3.0	1,760	20.5	29	15.7	2,620	4,380	600

A = rotor having normal resistance *B* = rotor having twice normal resistance *C* = rotor having 4 times normal resistance

istics and motor winding; but the net effect as regards heating of a given motor by using d-c braking over plugging is practically constant regardless of motor winding or rotor characteristic at a ratio of about 2.25:1 in favor of d-c braking. Greater liberality as regards heating, or a smaller frame size motor is thus permitted by the use of d-c braking for the deceleration cycle.

The above ratio is established from reference to table I, wherein the calculated kinetic energy of the rotating mass is converted to watt-seconds and added to the power input by both d-c braking and plugging.

It should be appreciated also that it is perfectly practicable to apply values of direct current to induction motors for the purpose of securing up to 4 times the braking effort that would be possible by applying full alternating voltages on a-c plugging. In other words, for duty cycle where the rate of deceleration is of primary importance but the running load and period for acceleration would permit of a lower torque motor, d-c braking is an entirely practicable solution.

Previous reference has been made to saturation effect preventing the effective braking torque from being a function of the square of the direct current applied, or a direct function of the d-c wattage. This is illustrated in figure 11, which shows the variation in watts per pound-foot braking torque for an 8-pole squirrel-cage motor with a semi-high torque rotor, taken over a 9:1 range. This particular case covers approximately $3^1/_2$ times the value of braking torque which would be secured by plugging this motor at full voltage.

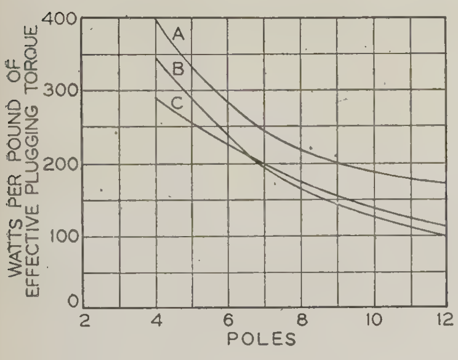


Fig. 10. Curves of a-c power required for a-c plugging of induction motors

A—Rotor having normal resistance
B—Rotor having twice normal resistance
C—Rotor having 4 times normal resistance

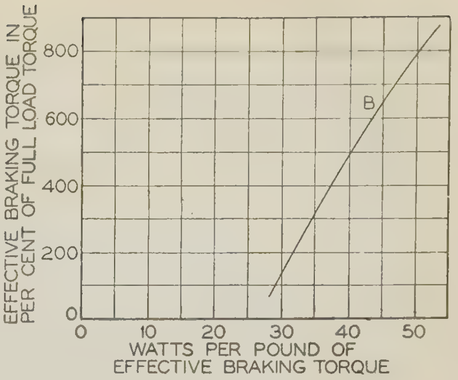


Fig. 11. Curve illustrating change in d-c power requirements with change in effective braking torque

Eight-pole squirrel-cage motor with rotor having twice normal resistance

Calculation of Current and Voltage

In conclusion, it may be in order to point out an approximate means of calculating the current and wattage necessary for d-c braking a given load in a given time, independent of the additional retarding effect of the friction and windage of the motor and its load.

The assumed case will be a 6 pole motor using a semi-torque rotor with a connected load having a moment of inertia (WR^2) of 300 pounds-feet-squared connected through a reduction ratio of 4:1 and running from a 60 cycle supply at 300 rpm. The motor and its load are to be stopped in 1.5 seconds. The motor has a terminal resistance of 2.8 ohms.

First it must be borne in mind that the inertia of the entire system must be referred to a common reference point, preferably the motor; second, that inertia transfer is accomplished through applying the square of the reduction ratio.

So to take the case at hand, the total inertia referred to the motor would be calculated as follows:

$$\begin{aligned}
&\text{Moment of inertia of load, } WR^2 = \frac{300}{4^2} &&= 18.7\\
&\text{Moment of inertia of motor rotor, } WR^2 &&= 1.5\\
&\text{Moment of inertia of gear, } WR^2 &&= 0.3\\
&\text{Total moment of inertia} &&= 20.5 \text{ pound-feet}^2
\end{aligned}$$

Referring to equation 2, the continuous braking torque is calculated as follows:

$$T = \frac{20.5 \times 1200}{308 \times 1.5} = 53.3 \text{ pound-feet}$$

Referring to curves in figure 9 giving a relation between poles, rotor characteristic, and watts per pound-foot torque for d-c braking for the subject case, a constant value of approximately 48 watts per pound is determined.

Then the power input to brake this load by direct current would be:

$$48 \times 53.3 = 2{,}560 \text{ watts}$$

Since watts equals I^2R, and R is the resistance between 2 terminals of the a-c stator, then the d-c braking current would be

$$I = \sqrt{\frac{\text{watts}}{R_t}}$$

$$I = \sqrt{\frac{2{,}560}{2.8}} = 30.2 \text{ amperes}$$

Thus, 30.2 amperes is the required value of direct current for the stator of this motor. To produce this current it is necessary to have a potential of IR_t or 30.2 × 2.8 equals 85 volts direct current.

Thus, it is deduced that a 2.56 kw input at 85 volts direct current applied to 2 terminals of the stator of a 6-pole semi-high torque rotor motor should brake it with its load in 1.5 seconds, irrespective of the friction which tends to assist in the braking effect.

The consideration of the strictly theoretical aspects which will lend themselves to calculation in order to predict accurately the full d-c braking speed-torque curves, may well be made the subject of further papers before the Institute.

Engineering Features of the Boulder Dam-Los Angeles Lines

Marking a new milestone in the history of the transmission of electric power, the 275 kv system that will transmit power from Boulder Dam to Los Angeles, Calif., embodies many novel engineering features. These features are discussed in this paper. The paper includes not only a description of the line and the terminal equipment and facilities, but also a discussion of the effects of the characteristics of each portion of the system on the performance of the system as a whole. The engineering studies and laboratory research on system stability, corona, high voltage impulses, lightning, conductor vibration, tower stresses, footing uplifts, and other factors are described, and the use of such data in the selection of line voltage, conductors, insulation, clamps, lightning protection, towers, and appropriate generating, transforming, and receiving end equipment is shown.

By
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THE Boulder Dam transmission system of the Bureau of Power and Light, Department of Water and Power, of the City of Los Angeles, Calif., will serve to transmit its allotment of power from Boulder Dam to Los Angeles, a distance of 266 miles, and consists of 2 60-cycle 3-phase circuits with a nominal line to line voltage of 275 kv. In the more or less built up section adjacent to Los Angeles, 40 miles of the line is carried on double circuit steel towers. The remainder of the line is carried on single circuit steel towers, with the conductors in horizontal configuration. Two sectionalizing switching stations are located at $^1/_3$ points.

Approximately 60 miles of the single circuit tower portion of line extends through mountainous territory, encountering 3 main mountain passes, at elevations of 4,862, 4,419 and 3,809 feet above sea level. Approximately 166 miles of the single circuit line is in desert territory of a hilly or flat topography, with a prevailing elevation of 2,000 to 3,000 feet. At least 225 miles of the line is subjected to the sparse and erratic rainfall associated with the desert. Such rainfall, at times, is of cloudburst proportions. The remainder of the line is in territory having the seasonal but somewhat limited rainfall experienced in the coastal plain of southern California. The desert section is subject to lightning storms at a frequency of 20 to 30 storm days per year.

The desire to achieve the utmost in high standards of continuous service, and the fact that this line will provide a relatively large portion of the total system power of the Bureau of Power and Light has made it necessary to regard reliability as the foremost consideration in the design of the line. A very liberal policy has been followed in conducting research to develop or verify and refine each step in the design of the line, and in establishing safety factors in order that the desired reliability might be assured. The newly developed features of the line, therefore, not only have a definite purpose, but have their performance well verified in advance by exhaustive investigation. The care in design has been carried on into the purchase and routine testing of the materials before they are incorporated into the line.

System Voltage and Equipment Characteristics

The earliest preliminary thought about this line centered on the use of 220 kv as the nominal rated voltage. At that time the state of the electrical art was such that the means of determining the dynamic stability or power limit of a transmission system had not been developed, and the proper method of determining the static power limit was a subject of discussion. It was realized that the most important factor in determining the voltage of the line was the power limit. In order definitely to obtain the required reliability, the ability of the system to withstand various types of disturbances without losing synchronism had to be determined. Such studies involve the terminal equipment and lay the basis for the selection of such equipment as well as line voltage. From a knowledge of the relative cost and the relative performance at each voltage, came the decision to use 275 kv.

In this work, methods of calculation were devised[1] that followed the fundamental theory set up in various papers on this subject[2,3,4]. Certain refinements were taken into account by setting up the circuits in terms of general circuit constants including all line characteristics and the exciting current and reactance characteristics of the terminal equipment. In addition, an approximate but fairly ac-

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1. For all numbered references see bibliography at end of paper.

curate method was devised of taking into account the characteristics of the load, by having the power component of the portion of the load admittance that represented induction motor load to increase inversely as the square of the voltage during disturbances, thus more closely representing the action of such load in consuming constant power, and drawing increased current as the voltage drops during synchronizing action on the system. Such motor load was assumed to comprise 40 per cent of the total load. In making these studies, the problem was reduced to a 2 machine problem, and the method of calculation was one giving results directly without making use of the point to point method of calculation and plotting time-angle curves.

Power limits are affected by many factors subject to variation, such as mechanical and electrical characteristics of the synchronous apparatus at each end of the line, frequency, voltage, spacing of conductors, location, type and duration of fault, number of sectionalizing points and manner and time required in switching faulted sections, nature of load, voltage drop between ends of line, reactance of transformers, and many other less prominent variables. As the preliminary work progressed, certain preliminary conclusions and assumptions became quite obvious and narrowed down the field to be investigated. These may be stated as follows:

1. The power limit is increased appreciably as the reactance between the internal voltages of the synchronous machine groups is reduced.

2. Corollary to the above, low reactance generators with large inertia effects were found to increase the power limit more than 40,000 kw, which justified the assumption of using the most liberal design of generators obtainable.

3. Sudden increasing of the reactance, such as occurs when a faulted line section is switched out, reduces the power limit very materially; hence it is essential that results be obtained principally for this case.

4. Three line sections are necessary, as the increase in power limit over that obtained by using 2 line sections is worth many times the investment in an additional switching station.

5. Within practicable limits, changes of spacing, diameter, or resistance of the conductors have negligible effects on the power limit.

6. Because of the effects of the equipment, the power limit varies almost directly as the transmission voltage, for lines of this length.

7. The fastest possible switching is exceedingly desirable to increase the power limit.

8. For the system arrangement contemplated for these lines, a fault near the sending end bus and involving one section of line to be switched out generally reduced the power limit to the lowest value.

9. Excepting for fault durations of less than 0.1 second the power limits for 3-phase faults are so low that it would not be considered economical to design the system to remain in synchronism for such conditions.

The rating of the system, that is its reliable transmitting capacity, of necessity depends on the criteria set up as to the type of fault that the system successfully must handle. Since a 3 phase fault is of exceptional occurrence and would be still less likely with reasonably rapid switching, and since it produced relatively low power limits, it finally was decided that the system would be rated on the load it could carry and not lose synchronism when subjected to 2 conductor-to-ground faults at the most unfavorable location, when the fault was removed by switching out a section of line in 0.2 second. When this switching duration was set it was considerably more rapid than generally seemed possible of achievement. However, confidence in this possibility was rewarded by switches and relays finally being supplied that will limit the fault duration to less than 0.11 second.

A single line diagram of a typical system setup is given in figure 1. Every element shown in the diagram was subject to variation in the study, which makes the tentative list of assumptions too long to include. The 2 groups of synchronous machines at the receiving end were combined into one equivalent machine. The load kept its separate identity.

In accordance with preliminary system studies,[5] it was desirable to transmit a load of approximately 240,000 kw to one receiving station. The first stability studies at 220 kv, using 2 circuits and 300,000 kva of low reactance generators, gave a theoretical power limit of the order of only 150,000 kw. If the generator ratings had been reduced accordingly, the value would have been still lower and more unsatisfactory. Further studies indicated that where under certain circumstances 3 220 kv lines would have a theoretical power limit of 280,000 kw, 2 275 kv lines would have a power limit of 265,000 kw and would transmit power at a cost per peak kilowatt of approximately 17 per cent less. Although more power could be transmitted by using a higher voltage, such as 330 kv, the use of such a voltage would result in excessive costs, because of the large diameter of conductor required, and would not be as economical per peak kilowatt. Since the 275 kv lines were the most economical and fitted in best with the desirable size of receiving station already established, this voltage was selected.

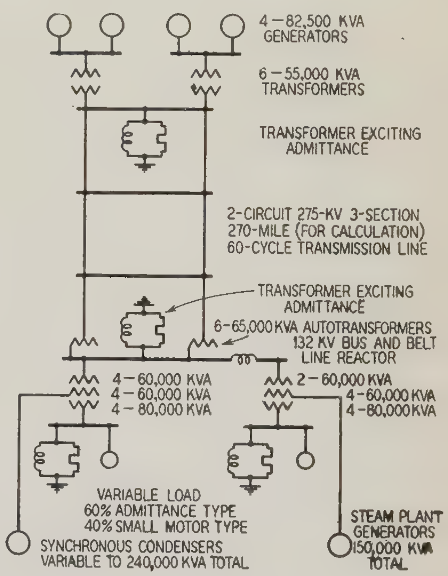
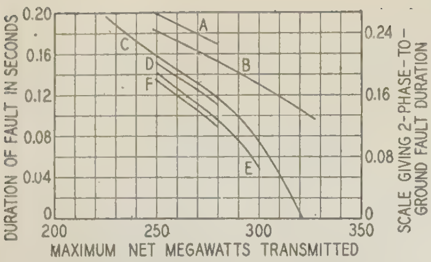


Fig. 1. Typical one line diagram of Boulder Dam-Los Angeles transmission system as used in stability studies

Sending End Equipment

The present system of the Los Angeles Department of Water and Power operates on a frequency of 50



Generator			
Curve	Per Cent Reactance	$WR^2 \times 10^6$	Sections Lost
A	20	110	0
B	20	81	0
C	20	110	1
D	20	97.5	1
E	25	110	1
F	25	97.5	1

Generator speed 180 rpm

Fig. 2. Stability curves for 60 cycle operation of system with a 3 phase fault at sending end

cycles per second. There were many reasons, from the standpoint of engineering and practical economics for both the system and the consumer, that made a change-over to 60 cycles attractive. If such a change were to be made, it obviously should be made at the time of bringing in such a large amount of new power. Other reasons, of a nonengineering nature, delayed the possibility of an early decision, so that much of the work had to be done for both frequencies and the earlier equipment specifications and purchases had to be made so as to permit the use of either frequency.

A typical set of stability curves for 60 cycle operation is shown in figure 2. All curves are for the condition where the fault is on a line section just out from the high voltage bus at the sending end. If no line sections are lost, the short circuit would be on the bus. All curves were calculated and drawn for the 3 phase fault condition as this saved considerable work in calculation and served for comparative purposes. In addition, a great many calculations for 2-phase-to-ground faults had indicated that for such a system as this, the permissible duration of a 2-phase-to-ground fault for the shorter switching times was 4/3 that of a 3 phase fault at the same load. The curves, therefore, were made to serve for 2-phase-to-ground faults by adding a new scale at the right-hand side of the graph, giving such approximate durations.

From the foregoing curves and other similar ones, were plotted the data given in figure 3, where the curves show power limits, in accordance with the criteria set up for line rating. For the particular system setup used, the inertia constant H used as abscissa is given by the relation[2]

$$H = \frac{4 \times 0.462 \times WR^2}{250{,}000}\left(\frac{\text{rpm}}{1{,}000}\right)^2 = 7.4\,\frac{WR^2}{1{,}000{,}000}\left(\frac{\text{rpm}}{1{,}000}\right)^2$$

where W is the weight of the rotating parts of one machine in pounds, R is the radius of gyration in feet, and rpm is the synchronous speed of the generator in revolutions per minute.

The lowest practicable transient reactance that could be obtained in designing a generator for straight 50 or 60 cycle use was about 21 per cent, while a generator suitable for operation at either frequency would have reactances of 21 and 17.5 per cent at 50 and 60 cycles, respectively, if the rating were held at the same value in both cases. The maximum value of moment of inertia (WR^2) that could be worked into the design was a function of the runaway speed of the water wheels, being larger for the lower speed. A tabulation of data for the 5 typical generators is given in table I.

An important point in the selection of the generators of table I is that the turbine used on the double speed machine has such dimensions that its maximum overspeed is lower than that of a single speed design with the same synchronous speed, which, together with the reduced reactance, gave a more favorable 60 cycle condition than a machine designed exclusively for 60 cycles. The frequency decision could not be settled at the time the generators were specified; however, as the most probable frequency would be 60 cycles, and as the power limit at 50 cycles was adequate, the double frequency machines fulfilled requirements very satisfactorily. As the switching time has been decreased from that shown in table I to 0.11 second, the power limits have been increased, still further. As these theoretical limits have no safety factor, the actual operating capacity has been fixed at 80 per cent of the theoretical figure to allow for imperfection of assumptions in calculation and to allow for general system hunting. Such rating is 235,000 kw.

In fixing the rating of the generators, one is faced with the fact that if the rating were made in exact accordance with the kilovoltamperes required for normal peak, the machines would be smaller than those of table I and no longer would permit the required power to be transmitted because of their higher reactance. Therefore, the method of obtaining low reactance consisted partly of using increased rating. This increased rating serves other functions, namely, stand-by capacity in the power plant and also for emergency operation, when because of failures in other power sources it is desirable to transmit larger amounts of power over this system, even at the risk of losing synchronism if a fault should happen. Such emergency rating is 300,000 kw delivered, requiring 4 82,500 kva generators for the 2 circuits.

The generators finally selected are 40-pole vertical water-wheel-driven machines, with main exciter and pilot exciter on the same shaft, and are rated 150/180 rpm, 13,800/16,500 volts, 50/60 cycles, 82,500 kw at unity power factor. They are provided with amortisseur windings and have the type of insulation designated as Class *B* on the armature and field. (Class *B* insulation consists of inorganic materials such as mica and asbestos in built-up form combined with binding substances.) At 50 and 60 cycles, respectively, the short circuit ratios are 2.28 and 2.74 and the transient reactances are not more than 21 and 17.5 per cent. The flywheel effect of each

Table I—Generator Characteristics and Power Limit for 5 Generators

Frequency, Cycles per Second	Per Cent Reactance	Speed, Rpm	Over-speed, Rpm	WR^2 Lb-(Ft)^2	H	Theoretical Power Limit/(KW) at 0.15 Sec
50	21	150	280	127×10^6	21.1	301,000
50	21	187.5	350	75	19.5	297,000
60	21	150	280	127	21.1	273,000
60	21	180	335	80	19.2	271,000
50/60	21/17.5	150/180	320	110	18.3/26.3	291,000/280,000

generator will be not less than 105,000,000 pounds at a radius of one foot. The load on the thrust bearing is of the order of $1^3/_4$ million pounds. The total weight of the generator is about 2,000,000 pounds. Because of the long time constant of such machines, and the rapid switching contemplated, there was no need for the highest possible rates of excitation, so the exciter response was set at 0.5. The over-all diameter is 40 feet and the over-all height above the generator floor line is 22 feet. The rating of the turbines under the minimum head of 420 feet is 90,000 horsepower, corresponding to a generator output of 65,000 kw, which with 4 machines provides for the normal reliable peak capacity of the line. However, as the head is increased larger outputs become available. For all heads in excess of 525 feet the turbine can deliver the full rating of the generator corresponding to an output of the turbine of 115,000 horsepower.

Two generators are connected to each transformer bank consisting of 3 55,000-kva water-cooled 287,500 Y/16,320-volt single-phase transformers. The high voltage windings are of the circular coil non-resonating type and are designed to withstand a $1^1/_2$x40 microsecond impulse voltage sufficient to flash over an 88 inch rod gap on the tail of the wave. The impedance is as low as practicable and will not exceed 10.75 per cent; the exciting current at normal voltage is 4.5 per cent and the full load efficiency is 99.31 per cent. The transformers each require a floor space 13 by 21 feet and their over-all height is 32 feet. The total weight of each transformer is 385,000 pounds of which 150,000 pounds is oil.

Receiving End Equipment

The generally accepted method of controlling transmission line voltage is to operate with fixed voltages at the sending and receiving ends. Voltage regulators for the generator hold fixed voltage either at the generator terminals or are compensated to the high voltage bus at the sending end. Synchronous condensers or other synchronous machines are required at the receiving end. The regulators for

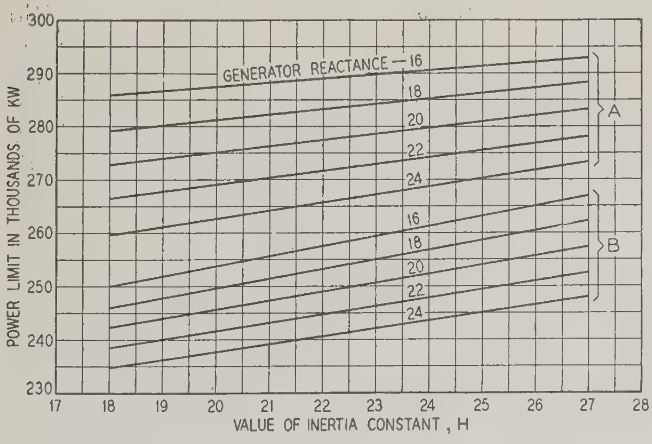


Fig. 3. Power limits of system for 60 cycle operation

A. Fault cleared in 0.15 second
B. Fault cleared in 0.20 second

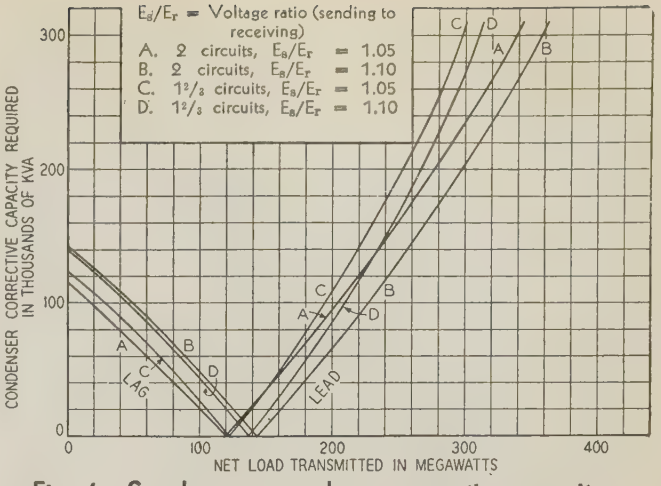


Fig. 4. Synchronous condenser corrective capacity required for operation at 60 cycles (transformers included)

these machines usually are compensated to hold fixed voltage at the load bus or the incoming voltage bus, depending on system connections. The exact amount or points of compensation have not been decided. Such methods of operation are equivalent to operating on a fixed voltage ratio circle on a receiving end circle diagram for the transmission line and equipment between the constant voltage points. From such a circle diagram, and the known characteristics of the system load, it is possible to estimate the required condenser capacity for all loads. Such a set of curves for the Boulder Dam system is given in figure 4. The curves are for full 2 circuit operation and for operation with one section out, designated as $1^2/_3$ circuits. The controlling points are the lagging requirement at very light loads and the leading requirement for the emergency rating of 300,000 kw delivered. Normal synchronous condenser design produces machines that have a lagging rating of 40 to 60 per cent of their leading rating. It is best, therefore, to select the voltage ratio between the 2 ends of the line of such value that approximately this adjustment is obtained. In this system the voltage ratio of 1.05 approximately does this and also approximately adheres to the established voltage ratings of equipment where the maximum operating voltage is 115/110 of the nominal. This latter ratio of 287,500 to 275,000 volts between sending and receiving ends was adopted. On this basis approximately 240,000 kva leading is required to deliver 300,000 kw and 115,000 kva lagging is required at zero load. There is the possibility that when emergency loads are being carried the voltage ratio can be increased, and approximately 200,000 kva of condenser capacity will be sufficient. This is very close to the requirement necessary to transmit the normal peak of 240,000 kw over the system with one section of one line out of service. At 50 cycles the requirements were about the same for high loads, but about 20,000 kva less lagging capacity was required at zero load. The capacity used to permit of the emergency rating essentially gives sufficient capacity to have the equivalent of a spare machine during ordinary operation.

The stability problem also entered into the selection of the proper equipment characteristics at the receiving end. For this purpose stability curves were plotted showing the effects of reactance of the autotransformers, reactance, and inertia of the condensers, location of fault, and fault duration. Some results were obtained without consideration of the auxiliary or stand-by steam plant.

The section of line at the receiving end included the same length of line as the other sections and, in addition, included the reactance of the autotransformers. Studies in connection with the generators had indicated that a sending end fault represented the worst operating condition. In studying the receiving end equipment, variations were made in such equipment and results obtained for faults at each of 3 locations, namely: sending end, losing adjacent line section; receiving end, losing receiving end line section; fault 180 miles ($^2/_3$ point) from generator, losing receiving end section. For any given setup, the sending end fault gave the lowest or controlling power limits or line ratings. The receiving end faults gave the highest power limits. The 180 mile fault gave limits slightly in excess of those for the sending end. For fault durations of the order of 0.1 second the power limits for the 180 mile fault were almost equal to those for sending end faults, and for quicker switching would be slightly less and thus establish the rating. For the switching times involved in this study, these results indicated that the proper correlation had been obtained in setting the electrical length or reactance of each section.

Decreasing the reactance of the autotransformers from 10 per cent to 7 per cent at 50 cycles increased the theoretical power limit 11,000 kw for sending end faults and about 15,000 kw for 180 mile faults, for the fault durations under consideration (0.14 and 0.11 second). For 60 cycles, decreasing such reactances from 12 to 8.4 per cent increased the power limits 14,000 and 20,000 kw, respectively, for the preceding 2 fault locations. Obviously such improvement is worth more than the increased cost of low reactance transformers so autotransformers of the lowest practicable reactance were purchased.

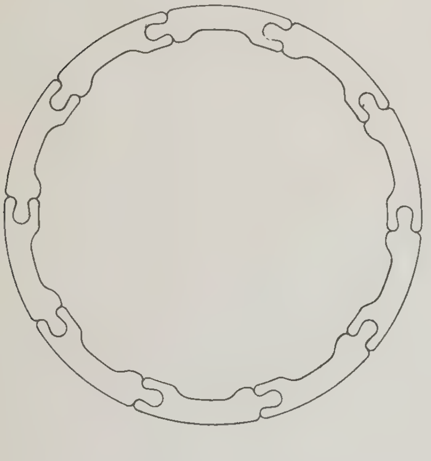


Fig. 5. Cross section of conductor selected

Area of cross section 512,000 circular mils
Wall thickness: maximum 115 mils; minimum 80 mils
Number of segments, 10

Two types of synchronous condensers were considered, one having a transient reactance of 35 per cent and a moment of inertia (WR^2) of 1,500,000 pounds at a radius of one foot, and the other having 50 per cent reactance and a moment of inertia of 1,250,000 pounds at a radius of one foot. In all cases, whether considered with or without auxiliary steam plant at the receiving end, it was found that the smaller high reactance machine gave the higher power limits. In either case the difference was small, being of the order of 3,000 kw. Under such circumstances, the lagging requirements controlled the selection of the condensers; and as the 50 per cent reactance machine satisfied these requirements, there was no object in purchasing more liberal equipment.

Within the range of the switching times considered, and for the final resulting system setup, the improvement in theoretical power limit is about 3,000 to 5,500 kw for each 0.01 second reduction in fault duration. On the basis of such improvement in performance, the selection of the most rapid switches, developed with an over-all switch and relay time of not more than $5^1/_2$ cycles, was made. With such switches the theoretical power limit in accordance with criteria previously referred to is 292,000 kw. A more detailed description of all the receiving equipment will be given in connection with the consideration of the receiving station.

Diameter of Conductor

For the voltages under consideration for this line, the primary consideration in the choice of conductor diameter is corona loss. In general, the diameter that will give an economical value of corona loss will be large enough but the amount of material required to construct such a conductor is likely to be more than is needed for conducting the currents that will exist in such a line.

No corona loss data were available for cables larger than approximately 1.1 inches in diameter.[6] Such tests indicated that existing corona loss formulas did not give accurate results for cables of such large diameter, particularly in the low loss portion of the curve which is the part a designer is most interested in. Accordingly, tests were made at the Ryan high voltage laboratory at Stanford University on stranded cables with diameters of 1.125, 1.49, and 2.00 inches to study the effects of diameter, condition of surface, spacing, atmospheric conditions, effects of cleaning, and other factors that would be pertinent to the selection of conductors for voltages ranging from 220 to 330 kv.[7] Further data on effects of surface conditions, temperature, humidity, and barometric pressure were provided by graduate student investigations in the same laboratory.[8,9]

Such laboratory tests cannot be conducted under exactly the conditions that will be encountered along the line, that is, the temperatures and barometric pressures will be different, as well as other less well known variables such as dust, humidity, and surface conditions. Furthermore, unless a great many cables were tested, it is likely that none of the sizes tested would be the final choice. In order to make use of fewer tests and in order to be able to make the design fit the line conditions, it was desirable to

derive a method of calculating losses that would agree with the tests and that could be used with some assurance for all the conditions anticipated along the line.[10]

A preliminary study of various designs of conductors was made to form the basis of an economic study to determine the proper conductor diameter to use. From data pertaining to the lighter designs, complete estimates of annual cost were made, after having determined the most economical combination of span and tension for each form and size of cable under consideration. The effects of conductor weight, strength, and diameter on tower and insulator costs were included, as well as those things directly pertinent to the conductor such as conductor cost, resistance, and corona losses. In this study the probable elevations and temperatures of the line were taken into account.

In the region of minimum cost, the annual cost of the conductor varies very gradually with the diameter. The corona tests had indicated that some uncertainties creep into the conditions that affect corona, so it is desirable to use some safety factor in the selection of the diameter. The economic choice in general comes near the knee of the corona loss curve. At such a point a small change in the uncontrollable and least known conditions makes large changes in the corona loss and could increase the annual cost possibly 30 per cent. Because of the relatively flat form of the cost curve, it was deemed advisable to be liberal by selecting a conductor diameter 0.1 inch larger than the theoretical but slightly uncertain diameter economy would dictate. From these studies the diameter of the conductor was fixed at 1.4 inches.

These preliminary corona and conductor studies provided appropriate information for making line estimates at various voltages when voltage selection was under way.

Type of Conductor

Conductor studies had indicated that when all features of cost were considered, the most economical cross section of a copper conductor of 1.4 inches in diameter was of the order of 500,000 circular mils, and that the maximum tension should be 40 per cent of the ultimate strength. The main influences on these values were those involving mechanical loading.

Essentially 6 different designs of cable were offered to meet the requirements of the line conductor:

Type *A*. A copper conductor weighing 2.226 pounds per foot, made up of a 7 wire strand surrounded by 6 twisted I beams with a single layer of round wires over all, this outer layer containing 30 wires each 0.125 inch in diameter.

Type *B*. A copper conductor, weighing 2.545 pounds per foot, made up with an inner structure composed of a central tube surrounded by layers of smaller tubes, with a single outside layer of 37 solid round wires each 0.104 inch in diameter; a variation of this conductor having thinner walled tubing and weighing 2.387 pounds per foot also was considered.

Type *C*. A hollow copper conductor weighing 1.57 pounds per foot, made up of 10 interlocking segments forming a self-supporting tubular structure; a similar conductor of heavier section weighing 2.3 pounds per foot also was considered.

Type *D*. An aluminum conductor, steel reinforced, weighing 1.852 pounds per foot containing 66 aluminum wires 0.1355 inch in diameter and 19 steel wires 0.117 inch in diameter; a conductor weighing 1.44 pounds per foot similar to this, excepting that a hemp filler of 0.213 inch radial thickness is used between 19 0.086 inch steel wires and 50 0.1355 inch aluminum wires, also was considered.

Type *E*. A copper conductor weighing 2.667 pounds per foot, of standard single-twisted I-beam construction, having 2 layers containing 66 wires 0.1077 inch in diameter.

Type *F*. A hollow copper conductor, weighing 1.80 pounds per foot, made up of 12 segments, grooved to take an oval wire acting as a tongue between adjacent segments.

Typical cross sections of these various cables are shown in figure 1 of a paper entitled "Corona Losses From Conductors of 1.4 Inches in Diameter." [11]

In selecting the conductor, comprehensive and accurate estimates of annual costs were worked out

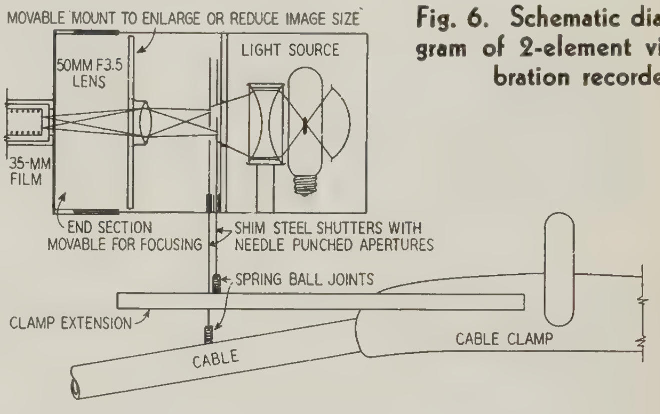


Fig. 6. Schematic diagram of 2-element vibration recorder

for each type for various tensions and span lengths, so that comparisons would be made between the most economical uses of each type. The lighter conductors showed savings of the order of $12^1/_2$ per cent over the heavier types, partly due to conductor price and partly due to the higher cost of towers and supports for the heavier conductors.

Comparative corona tests were made[11] and type *C*, the interlocked segmental type of hollow copper conductor, showed the lowest losses and preferable characteristics, although all conductors, as was anticipated, had low losses at the operating voltage, even with some allowance for elevations.

Because of the low weight for the diameter involved in all these cables, it was thought necessary to give due regard to the tendency for conductors to vibrate in light winds[12, 13, 14]. As a preliminary test to assist in the selection of conductors, a wind tunnel was used that provided an orifice 50 feet long and 2 feet high which was so baffled and controlled as to produce a quite uniform wind velocity across cables hung in front of the opening. In this manner the tendency of the cable to vibrate under the same type of forces and at the same tensions as in actual practice was simulated closely. Although from its diameter-weight relation, the light hollow copper cable might be expected to give greater amplitudes under such conditions, it actually gave the same amplitudes as the heaviest I beam type of conductor; this indicated a considerable degree of self-damping, a fact that was confirmed by later tests.

These data together with the successful operation of similar cables in Germany, led to the selection of the cable as previously described under the designation "type *C*"; a cross section of this cable is shown in figure 5. The copper area is 512,000 circular mils. As a permanent lubrication between segments, graphite is introduced between the surfaces of the interlocking tongue and groove. The exterior of the cable is washed and cleaned thoroughly as was indicated to be necessary from the corona tests. The ultimate guaranteed tensile strength is 21,600 pounds.

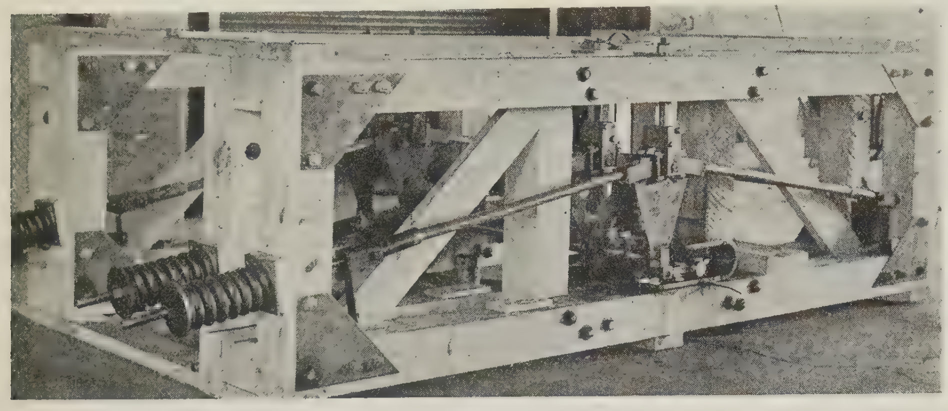


Fig. 7. Cable testing frame for studying bending properties of conductor

VIBRATION STUDIES FOR CLAMP DEVELOPMENT

Having selected the cable, the next procedure was to determine accurately all the vibration characteristics of the cable, in order to ascertain what features had to be incorporated into the design of the clamps to be used therewith so that the possibility of fatigue failures would be eliminated. It had been decided to follow this program irrespective of what type of cable had been purchased for the line, as it was believed that the large diameter entered into a new range of stress relationships that had a bearing on fatigue failures.

The wind tunnel tests were continued, to introduce refinements and perfection of technique and to study the effects of variation in tension. As a standard of comparison, tests were made also on the 1.00-inch double-layer I-beam type of conductor used by the Pacific Gas and Electric Company, for which a considerable amount of field data was available.[12] It was not found possible to obtain as large amplitudes as found in the field, possibly because of the absorption of energy at the ends being large with respect to that imposed by the wind on such short lengths of cable.

The tendency of the cable to vibrate in conformance with recent theory as regards frequency and loop lengths was established. Where the wind frequency was not exactly resonant with possible loop frequencies, beat note effects were observed due to the nearest possible loop frequencies. There was a marked increase in vibration amplitude at any given wind velocity or air eddy frequency as the conductor tension was increased.

Because the tunnel tests apparently did not produce as high amplitudes as would be obtained under actual operating conditions, it was decided to make measurements on actual full length spans with natural wind. A site near one of the construction camps was selected as being most favorable for producing such vibration. The country is of even topography for many miles either side of the line and the prevailing winds are at right angles to the line. Standard suspension towers (3) were used to support 2 full spans; 100 feet beyond these towers temporary poles were erected for dead end connections. The recording devices were installed at the middle tower. Records of vibration were obtained for 2 values of normal tension, 4,350 and 6,500 pounds.

For obtaining the vibration records 2 photographic recorders were used. One recorder having a single element records the movement of the conductor 6 feet from the center of the suspension clamp, indicates time in 5 second intervals, and shows the direction and velocity of the wind. The other recorder has 2 elements and records simultaneously the movement of both the conductor and the suspension clamp, at a point $15^1/_4$ inches from the center of the clamp; 5 second intervals also are recorded. The purpose of this record is to show the relative bending between the cable and clamp.

Records are taken on standard moving picture film, run at a normal speed of one foot per minute, with the additional provision that the 2 element recorder automatically makes a 5 foot record at 10 times normal speed every 15 minutes of normal operation. The recorders are mounted on a platform which replaces the insulator string and is pivoted to move similarly in the wind. The alignment between cable, clamp, and recorder accurately is preserved for all wind conditions. A schematic sketch of the installation is shown on figure 6. In addition to the parts shown, the installation is equipped with an initiating device that permits the recorder to be shut down except when the vibration exceeds a predetermined amplitude.

The principal conclusions that might be drawn from these records are as follows:

1. The conductor vibration is extremely variable and complex showing considerable beat note phenomena or superposition of loop lengths.

2. With few exceptions, vibration of importance occurs at very low wind velocities, less than 6 or 7 miles per hour.

3. The portion of the total time that the cable has appreciable vibration is of the order of 3 to 5 per cent for the lower tension and 12 per cent for the higher tension.

4. The maximum angle of cable movement at a node point is 0.27 degree for the lower tension and 0.49 degree for the higher tension.

5. The maximum angle of relative bending between cable and clamp, when the phase relations are such that the cable is moving the same direction on each side of the clamp, is 0.033 degree for the lower tension and 0.132 degree for the higher tension.

In order to study the bending properties of the cable, tests were made using the rack shown in figure 7. For this test the cables were run over simple radius clamps of various radii from 28 to 42 inches. A keeper was bolted down to clamp the cable in place and the clamp was oscillated by the eccentric and connecting rod shown in figure 7. As the samples were short, care was taken to equalize the tension on each segment.

The essential conclusion drawn from this test is that for any radius longer than 28 inches, the conductor will have an indefinitely long life when the relative movement between the conductor and clamp does not exceed an angle of 0.4 degree, while at double this angle the life of the cable is very short. The actual relative bending encountered on the line is only about $^{1}/_{12}$ of that which the rack tests indicated would give long life.

In another set of tests, various suspension clamps were set up in a normal position between spans one per cent different in length. These spans were vibrated by means of 2 eccentrics with the same percentage difference in their frequencies. This successively subjected the clamp to in-phase and out-of-phase vibration at the 2 ends. A recorder, similar in principal to that shown on figure 6, was used to measure the relative movement of the cable and clamp. It was found that for those clamps that provided for trunnion action at or near the center line of the cable, the relative bending between cable and clamp was about 80 per cent of that obtained with clamps pivoted or hung approximately 2 inches above the center line of the cable.

Clamp Design

As a result of various facts ascertained from the cable vibration studies and detailed analysis, a suspension clamp of novel design was evolved, known as the free-center type, shown in figure 8. It consists of an outer housing or shell supported by knife edge trunnions on strap hangers. The shell in turn provides knife edge support for 2 saddles in which the cable rides. These knife edges are $^{1}/_{2}$ the cable spiraling pitch apart. The malleable cast shell is of a form that will avoid formation of corona. The saddles are die cast of bronze to avoid corrosion and to give a supporting surface free from pits, projections, and blemishes in which the curvatures could be controlled accurately within very small tolerances. Attached to the cable and normally free from the clamp is a center clamping piece consisting of a double conical wedge adjacent to the cable, which fits into the 2 halves of the clamping piece. In the event of a cable breaking, the central clamping piece engages bosses at the center of the shell, whereupon the conical wedge exerts clamping action on the cable and develops strengths in excess of 8,700 pounds.

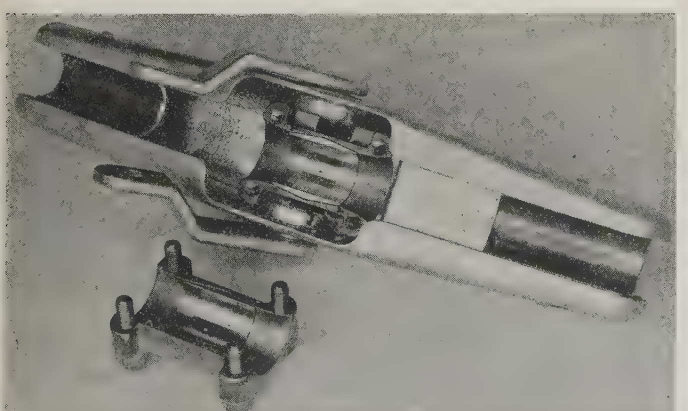


Fig. 8. Free-center suspension clamp

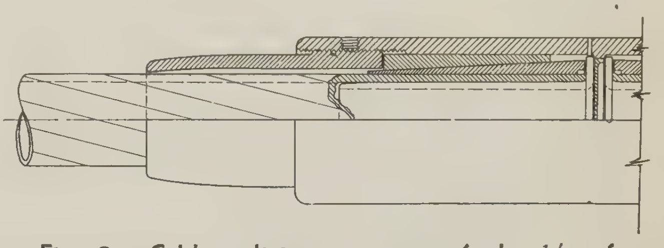


Fig. 9. Cable splicing connector (only $^{1}/_{2}$ of connector is shown)

With this type of suspension clamp, the bending of the cable resulting from vibration is not localized at one point, but is distributed essentially on nearly uniform curvature over a full pitch length, thus avoiding any concentration of bending stress on any one segment or single place in the cable. At points where the bending is taking place there are no superposed stresses due to clamping action.

All principal dimensions of the clamp parts were determined by special tests including such things as location of trunnion points, saddle pivots, curvature of saddles in both directions, length of saddles, and dimensions of parts in the center wedge system.

Clamp Life Tests

During the progress of the design of the clamp and after the final design, life tests of this clamp together with other types of clamps were made and are still in progress. Such tests were made by driving the cables on both sides of the suspension clamp by means of an eccentric attached to the cables approximately 6 feet from the clamp. In order to produce maximum bending for a given deflection of the cable and to avoid any trunnion action that would reduce the bending, the cables on each side of the clamp were driven in the same direction simultaneously. In this manner, without using unusual speeds or amplitudes, the fatigue failures could be tested with the kind of maximum bending that occurs for only a

part of the total time of vibration in actual service where considerable trunnion action takes place.

By means of such tests, refinements were made in the free-center clamp. The superiority of this type of support over more conventional types of clamps was demonstrated. There is every assurance that can be afforded by laboratory testing and field investigation that the line should be free from any difficulties arising from fatigue failures.

Connectors and Strain Clamps

In accordance with the specifications for the conductor, a suitable means of splicing had to be furnished with each length together with extra connectors for making field splices. The type of splice provided with the hollow conductor is that shown in figure 9. It consists of an inner supporting tube inside the conductor, and a double split wedge assembly that grips the conductor tighter as the pull is increased. The pulls are transferred to an outer sleeve by the threaded members at the ends. The radial wedge pressures also are borne by the outer sleeve. Refinements have been introduced in the wedges so that the intensity of grip is increased as the inner edge of the wedge is approached; also the outer threaded members are so shaped as to limit the bending of the cable that can occur at the wedge entrance so that vibration cannot cause a concentration of stresses at such a point. The connectors are made of high strength bronze, so as to be free from corrosion, and have accurate smooth surfaces and sufficient strength with light weight. The light weight is essential in order to avoid large bending stresses while the vibrating cable is accelerating the connector.

The dead end connector is similar to the splicing connector except that one half of the connector is replaced by a screw clevis fitting, shown in figure 10 (part *A*). A similar fitting with a single wedge (part *B*) is used for the jumper loop connecting the 2 dead ends on opposite sides of the tower arm. The jumper loop clamp and the strain clamp are interconnected by flexible copper braid of 307,000 circular mils, as a shunt around the mechanical interconnection provided by the yoke.

Insulation and Lightning Protection

For purposes of insulation design, the line is divided into 2 main sections as regards its exposure. The section from Cajon Pass to Boulder Dam (a distance in excess of 200 miles), which is on single circuit towers, can be considered as the lightning section, with lightning storm days probably not exceeding 30 per year. The insulation scheme for this section is based almost entirely upon lightning considerations. From Cajon Pass to the receiving station, the remaining section of the line 40 miles of which is on double circuit towers, the lightning storm frequency is of the order of 5 storm days per year. This section will be subject to troubles from insulator leakage that arise from dust accumulated during a long dry season followed by fog and rains, with the accompanying noise and flashing over of single units, at times involving the possibility of string flashovers at normal voltages or switching surge voltages.

Engineers of the Los Angeles Department of Water and Power have profited very considerably from a study of the results obtained from lightning research being carried on by various power companies and electrical manufacturing companies [15–22]. Consideration of the data obtained from such studies made it almost self-evident that in order to limit the number of flashovers per year to a small value compatible with the reliability desired for this line, 2 overhead ground wires per tower line should be used and probably some type of buried ground wire or counterpoise system as well, in lieu of trying to establish any other satisfactory form of tower footing grounds in such dry desert territory.

Studies indicated that lightning can be expected to strike with about equal frequency the transmis-

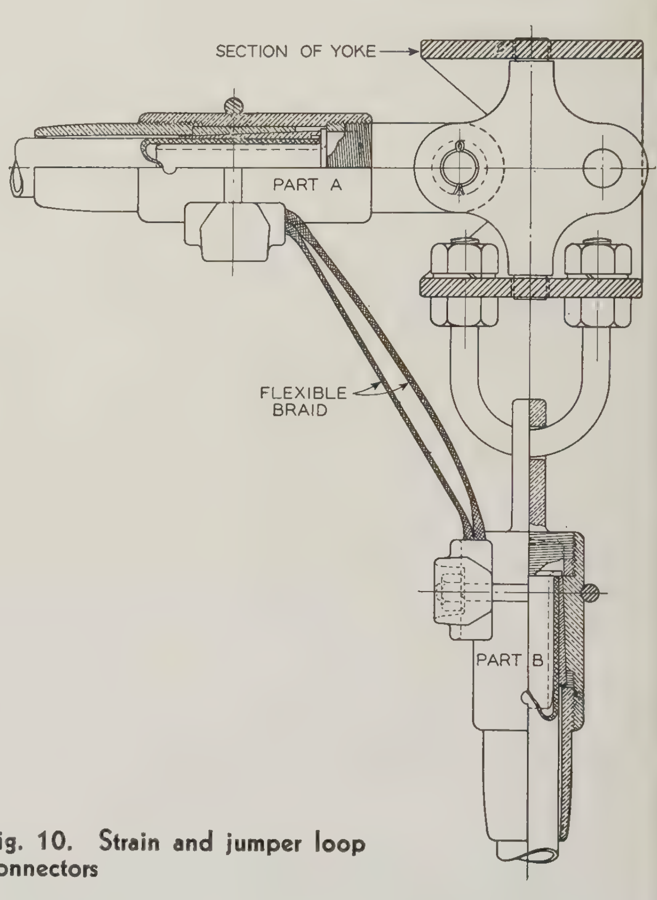


Fig. 10. Strain and jumper loop connectors

sion towers and the overhead ground wires. The danger of flashover of the insulator string is greatest when lightning strikes the tower. The danger of flashover between a ground wire and a conductor is greatest when lightning strikes the ground wire at the center of the span. Spacings at these points should be co-ordinated to withstand the same lightning streamer voltage.

In the selection of the insulator string length on a lightning basis, the voltage of the line has small influence; however, to hold the danger of a power arc following lightning flashover within limits prescribed by existing practice, it was deemed advisable

to increase the string length in proportion to the voltage over the present trend in 220-kv line insulation. This gave a length of the order of 120 inches. This same string length was confirmed for the section affected by dirt and fog.

The dirt and fog problem was studied at the Ryan high voltage laboratory, where a wind tunnel was arranged so that controlled wind would carry dust and fog alternately past insulators while voltage was applied to them. The object of this test was to find insulator shapes that would be superior for the purpose and to determine the desirable number of units to use to reduce trouble from this source. These studies indicated a distinct advantage in using relatively long strings of closely coupled insulator units, such as 10 inch units with 5 inch spacing.

In selecting the insulator units for the single circuit tower section, the cost of the insulator units and the increased cost of towers necessitated by those units requiring longer strings to develop the same impulse flashovers were taken into account. It was found most economical to use suspension insulator units 10 inches in diameter, with a hanging distance or pitch of 5 inches; 24 such units constitute a standard suspension string for both the single and double circuit tower sections. For suspension strings carrying heavier loads because of horizontal or vertical line angles, 22 suspension insulator units $10^1/_2$ inches in diameter with 6 inch pitch are used. For dead end positions on the single circuit towers, double strings of 22 $10^1/_2$ inch units with 6 inch pitch are used. For dead end positions on the double circuit towers where the maximum pulls were reduced by the type of loading assumed, double strings of 24 10 inch units with 5 inch pitch are used. The insulators are of resilient pin construction. The light duty insulators have a mechanical and electrical ultimate strength of 11,000 pounds, while the heavier duty insulators have a similar strength of 15,000 pounds.

Clearances

In establishing clearance distances from the conductor or other parts at line potential to the tower, it was desirable that arcs be confined between arcing horns, which are to be provided at each end of the insulator strings, rather than between conductor and tower. However, it was realized that this ideal would not be economical to achieve at the highest wind velocities assumed in the mechanical design of the line. The highest wind velocities would endure for such a small part of the life of the line that it was thought reasonable to have an impaired clearance under such circumstances. At the time it was necessary to set clearances for tower design purposes, the question of arcing horns had not been investigated completely so a fairly liberal size was chosen, 30 inches in diameter in the plane of swing (suspension type) placed one foot above the conductor.

For all wind pressures up to 4 pounds per square foot (about 40 miles per hour) a full clearance of 11 feet to the tower is maintained, which is about 10 per cent in excess of the point-to-plane arcing distance equal to the insulator flashover. The conductor then is placed at its extreme position under a wind pressure of 12 pounds per square foot. At this position a clearance of 7 feet is maintained. The outer boundaries of the figures described by these radii constitute the clearance diagram. The 7 foot flashover distance corresponds to approximately $4^1/_2$ times normal voltage, which is considered to be protection against switching surge flashovers. The same fundamental clearance diagram assumptions are applied to each type of tower. These clearance diagrams resulted in a horizontal spacing of 32.5 feet for single circuit towers, and a horizontal spacing of 40.5 feet and a vertical spacing of 24.5 feet for double circuit towers.

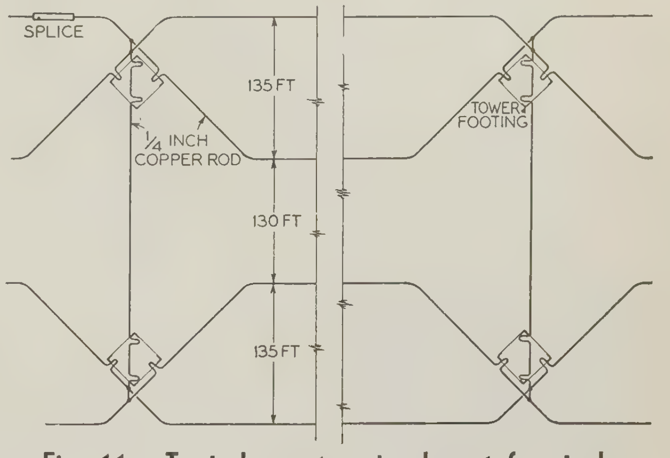


Fig. 11. Typical counterpoise layout for single circuit tower section of line

Overhead Ground Wires

For the single circuit tower section, each tower line is protected by 2 overhead ground wires of $^1/_2$-inch 7-strand galvanized wire with a guaranteed ultimate strength of 18,800 pounds. At the towers the ground wires have a horizontal separation of 50 feet and are 32 feet above the main conductors, while at the center of the span they are 40 feet above the conductors. Two wires are used because of the advantages resulting from the decreased surge impedance, the increased coupling factor to the conductors, a more balanced relation to each conductor, and, most important, because of the more complete and reliable shielding of the conductors from lightning streamers, without going to unreasonable heights. Surge calculations indicated that co-ordination of flashover across an insulator string caused by a stroke hitting a tower, and a similar flashover caused by a stroke hitting a ground wire at mid-span, required that the spacing between conductor and ground wire be 40 feet. Economical tower design then led to the location of the ground wire attachment at the tower about 32 feet above the conductor. It was thought that such height should give very reliable shielding. Too high ground wire pulls at such heights were quite uneconomical.

Steel wire of a size that will meet the mechanical requirements of the line has more than adequate conductivity from the standpoint of lightning protection. Investigations in other similar desert areas had indicated that over very long periods of time the corrosion of such wire was negligible. With this in mind the material having the lowest cost, steel, is used in this section. On the double circuit tower section there is more likelihood of corrosion occurring, because of moisture and fog conditions in the coastal plain section. For this reason, copper covered steel wire is used; this wire consists of 7 strands, is $^7/_{16}$ inch in diameter, and has a strength of 18,500 pounds and 30 per cent conductivity. Two ground wires are used, mounted in the same vertical plane as the conductors, and at heights above the conductors similar to those of the steel wire on the single circuit towers.

Fig. 12. Typical suspension insulator assembly

BURIED COUNTERPOISE

Successful operating results achieved by a few power companies as a result of very limited installation of counterpoise at exposed positions,[20] made it attractive to consider the extensive use of the counterpoise for this line, where grounding conditions are particularly severe. A large part of the desert soil is gravel, sand, or both, with the water table in general measured in hundreds of feet below the surface and with an annual rainfall of the order of 3 inches. In such high resistant earth, the counterpoise serves to provide a low impedance conducting system to permit the lightning discharge to terminate at the opposite charges on the surface of the earth under the cloud area. As an outcome of the studies, the counterpoise was installed in the single circuit tower sections as shown on figure 11, giving 2 continuous counterpoise wires for each tower line with cross ties at each tower between circuits. The 45 degree spreading at the towers was adopted to obtain the low surge impedance advantages of the radial type of counterpoise, and the continuity of the counterpoise eliminated the possibility of end reflections from such points of discontinuity in the purely radial counterpoise. The continuity also has advantages in permitting the fault currents to be large enough to avoid too much difficulty in relaying the line at points distant from power sources. The particular pattern adopted also facilitated the laying of the counterpoise by means of a specially devised plow and counterpoise laying machine.

Table II—Effect of Tower Footing Impedance on Lightning Streamer Crest and Flashovers

Tower Footings Impedance, Ohms	Lightning Streamer Crest, Volts	No. Flashovers per Year per 100 Miles of Circuit
17	18,500,000	0.5
21	16,000,000	0.75
27	13,500,000	1.1
38	9,000,000	2.9

The wire used for the counterpoise is $^1/_4$-inch diameter black rolled copper rod. This diameter was adopted as representing the smallest size that might be expected to withstand corrosion for the life of the line and be mechanically strong enough to withstand the stresses involved in laying the wire. The softness of the rolled copper was also an advantage in handling.

From test data that were available[21] some judgment could be formed of the value of the counterpoise. Theoretical values of surge impedance required the use of a large dielectric constant for the soil in order to agree with the tests. By using such a constant and making allowance for corona effects caused by the higher voltage on such wires resulting from natural lightning, estimates of surge impedance were made. All factors entering into the calculation of surge impedance of counterpoise systems are not fully understood, and no method of calculation has met with universal approval. However, this does not deprive one of the advantages of making comparisons in terms of definite relative figures, even though the actual accuracy of such figures is subject to limited doubt. Taking into account the surge impedances of the lightning stroke, ground wires,

and counterpoise system, and the coupling effects between the ground system and the main conductors, the crest voltages of the oncoming lightning wave in the streamer were calculated for various tower footing or counterpoise surge impedances as shown in table II. In this table are included also the numbers of flashovers per year per 100 miles of circuit for a region having 30 lightning storm days per year.[19] For comparison with these values, the surge impedances of various combinations of continuous counterpoise wires were estimated as follows:

1 tower line, 1 counterpoise wire....................38 to 50 ohms

2 tower lines, 1 counterpoise wire each, cross-connected....................................27 to 40 ohms

1 tower line, 2 counterpoise wires....................21 to 30 ohms

2 tower lines, 2 counterpoise wires each, cross-connected....................................17 to 25 ohms

Considerations of reliability and relatively low cost of counterpoise compared with other methods of obtaining equal protection, that is, by use of additional insulators, dictated a choice of 2 counterpoise wires per tower line, cross-connected in the single circuit tower section. In the double circuit tower section, the lightning storm frequency is much lower so the double counterpoise for a single tower line will give excellent performance there.

In connecting the counterpoise wires to the towers, it was considered inadvisable to attach the copper directly to the towers because of the possibility of electrolytic action between the copper and steel corroding the tower footing steel. Consequently, attachment is made through a spark gap that is essentially 2 concentric bronze cylinders with a $^1/_{16}$ inch air gap. A very small percentage of any fault potential will be capable of arcing over the gap and bring the counterpoise into action.

Transpositions

A complete transposition "barrel" is arranged within the sending end section and the middle section of the line. Transposition towers are, therefore, approximately 30 miles apart. Another complete "barrel" is arranged in the single circuit tower portion of the line beyond the second switching station. The double circuit portion of the line, because of communication line interferences, has 3 complete transposition "barrels" of 13, 4, and 23 miles.

Hardware

Aside from the suspension and dead end clamps that were discussed in connection with the conductor, the 2 main items of hardware to be considered are the arcing protectors and the dead end yokes. The principal functions of the arcing protectors is to avoid cascading of the insulators and burning of the conductors.

The arcing horns adopted for suspension type insulator strings consist of a twisted and bent $^3/_8$x$1^1/_4$ inch strap arcing horn at the top or grounded end of the string and a "figure 8" horn of bent $1^1/_4$ inch pipe at the bottom of the string as illustrated in figure 12. For the dead end assemblies, each yoke carries on its top side an arcing horn made of bent $1^1/_4$-inch pipe, as illustrated in figure 13.

These particular forms of arcing horns were developed in the high voltage laboratory of the Ohio Brass Company with the assistance and co-operation of the engineers of that company. Impulse voltage tests were conducted on these devices for the purpose of determining the maximum separation, with the most favorable location of each horn tip, that could be obtained and have all arcs form between the horns and not cascade over the insulators. Similar tests also were conducted at an earlier date at the high voltage laboratory of the General Electric Company on the oval ring type of shield. Both types of shields as finally developed by these tests gave satisfactory performance in both flashover and protection from cascading. The greater tower clearances and the economy of the simpler horn types led to their adoption.

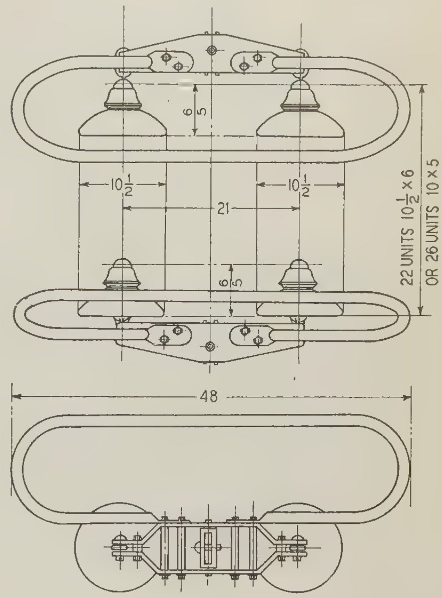


Fig. 13. Typical strain insulator assembly

All dimensions are in inches; string lengths show diameter and spacing of individual units

In the yokes, which also are illustrated in figure 13, 2 new features of design have been incorporated: approximately a 50 per cent increase over standard practice in the distance between strings, and a short offset distance between the pin for the strain clamp and pins for the ball and socket fittings to the insulators. The distance between strings was set at 21 inches to try to avoid the possibility of cross-flashing of strings because of the poor voltage distribution that occurs under dirt and moisture conditions. The short coupling distance mentioned is to obtain a long natural period of vibration in the vertical plane, so that the yoke will not be set in harmonic vibration within the range of vibrations existing on the conductor and thus introduce special bending forces at the entrance of the cable into the dead end clamps.

The width of opening of the yoke is to accommodate the dead end clamp in the position it will take if one string of insulators should break. The central inner clevis of the yoke, to which is attached the dead end clamp, has on its opposite side another

clevis opening to which can be attached a strain bar with turnbuckle arrangements connecting to a similar clevis at the other yoke, so that tension can be removed from the insulators and the whole insulator and yoke assembly removed for maintenance work without affecting the conductor. The yoke members are of $^1/_2$ inch steel plates 5 inches wide at the center, and the complete yoke has an ultimate strength of 30,000 pounds.

The jumper loop at the dead ends is hung from a U bolt underneath the yoke. Its suspension is independent of the main conductor so that its swing angle will not be influenced by the wind movements

Fig. 14. Ground wire strain clamp

of the main conductor and thus require more clearance space. The jumper loop is stiffened by the insertion of a 20 foot length of $^3/_4$ inch (iron pipe size) extra heavy copper tubing, so that it can be bent and held to the proper form to give clearance under the tower arm. This added weight reduces the swing of the loop caused by wind. The electrical connection is made by means of the braid previously described.

Special clevises and attachments were designed so as to keep the string lengths to a minimum.

At all suspension towers, the ground wire is supported on standard trunnion type suspension clamps. At all towers of special strength, the ground wire is connected by means of a special strain clamp illustrated in figure 14. This clamp is designed to have an ultimate strength of 20,000 pounds, and is a modification of existing types of clamps in order to develop increased strength. This type of clamp was selected primarily in order to have a clamp that would have a high natural frequency of oscillation, so that it would follow the natural vibration frequencies of the ground wire without causing large relative bending between clamp and cable at the entrance.

Single Circuit Towers

A diagram of a typical standard suspension tower is shown in figure 15. Exclusive of the footing steel, this tower weighs 18,100 pounds. It is designed for use on 1,000 foot spans and has a height to the cross arm of 90 feet. Its over-all height is 109 feet. It may be modified by leg extensions in 10 foot intervals up to 40 feet, none of which need be equal. Where very short towers are desired, the portion of the tower below the "waistline" is omitted. The tower is of the narrow waisted type with a rotated base, that is, the base is rotated 45 degrees with respect to direction of the line. The types of towers are standard suspension, angle suspension for vertical and horizontal angles that can be taken on the heavy duty suspension insulator strings, strain towers for all large angles and other points where such construction is required, and transposition towers which accomplish the transposition of conductors at one tower. All towers are of the same general appearance and have the same system of lower leg extensions.

The total number of single circuit towers in 225.3 miles, of double circuit line is 2,422, producing an average span of 984 feet. The longest span is 1,811 feet and the shortest 431 feet.

All single circuit towers are designed for the loadings imposed by $^1/_2$ inch radial thickness of ice on the conductor, with a wind pressure of 8 pounds per square foot of projected area at 10 degrees Fahrenheit. Under such circumstances the stress in the conductor is 40 per cent of its ultimate strength, or 8,700 pounds. The height of the towers is such as

Table III—Tower Design Stresses

	Stresses in Pounds per Square Inch	
	Structural Steel Grade	High Elastic Steel Grade
Axial tension on net section	20,000	22,500
Axial compression on gross section for L/R ratios of 60 to 150	20,000–85 L/R	25,350–110 L/R
Axial compression on gross section for L/R ratios of 150 to 200	15,500–55 L/R	17,400– 57 L/R
Maximum compressive stress	15,000	18,750

to give a minimum center span clearance to the surface of the ground of 27 feet at a conductor temperature of 150 degrees Fahrenheit with no wind. The normal tension at 60 degrees is 4,370 pounds. Under similar loadings the maximum ground wire tension is 5,000 pounds, with a normal tension at 60 degrees of 1,800 pounds.

Suspension towers are designed to withstand 1 broken conductor and 1 broken ground wire simultaneously under maximum tension in the same span on the same side of the tower. Angle suspension towers, used where small horizontal or relatively large vertical angles are encountered, are designed to withstand under maximum load 3 broken conductors and 2 broken ground wires on the same side of the tower. Strain towers, used at large horizontal angles and other points of special nature requiring dead end construction, also are designed to withstand 3 broken conductors and 2 broken ground wires on one side of the tower. The towers are designed also for the torques imposed by the worst case of other combinations of the specified broken wires. The wind load on the towers was specified as 20 pounds per square foot on $1^1/_2$ times the net projected area of one face of the tower.

The towers are built largely of steel having a high elastic limit. The schedule of design stresses is

given in table III. The slenderness ratio (L/R) was not in excess of 135 for leg members and 200 for web members. (The slenderness ratio of a compression member is the ratio of its unsupported length to its radius of gyration.)

In response to the specifications, several types of towers were offered embodying conventional designs, narrow waisted type, and narrow waisted type with rotated base. The latter design was slightly lighter in weight, had advantages from the standpoint of smaller footing reactions, and was less costly—hence its selection.

Double Circuit Towers

A diagram of a typical double circuit suspension tower is shown in figure 16. Its height to the bottom crossarm is 75 feet, and its over-all height 144 feet. It weighs 23,000 lbs. This tower with extensions in multiples of 10 feet, is used on normal spans of the order of 850 feet in the populous territory adjacent to the City of Los Angeles, where the minimum clearance to the ground is maintained at 45 feet. The tower is of the conventional double circuit type, and has the same general classification of towers as the single circuit type. The total number of double circuit towers in 40.8 miles is 257, giving an average span of 839 feet. The longest span is 1,620 feet and the shortest 331 feet.

Double circuit towers are designed for a maximum pull of 8,700 pounds. The wind loading on the conductor at maximum tension is assumed at 12 pounds per square foot of projected area, with no ice and a temperature of 25 degrees Fahrenheit. The broken wire assumptions are 1 conductor and 1 ground wire broken for suspension towers, 3 conductors and 2 ground wires broken for angle suspension towers, and all 6 conductors and 2 ground wires broken for the strain towers. The basis of design is the same as for the single circuit towers.

Footings

All towers are provided with reinforced concrete footings of the pad and pedestal type, set in an undercut excavation so as to develop uplifts in largely undisturbed soil. A series of footing stubs of different lengths, capable of further limited length adjustment, were designed to take care of various depths of footings to meet conditions imposed by differences in soil, slope of the ground, and soil erosion. The footings were designed for bearing, uplift, shear, bending caused by shear, and punching. The uplifts are computed on a 30 degree cone basis. In connection with the footing design, full sized footings were set in various types of soil and pulled to failure. Those in uniform soil indicated quite close agreement with the 30 degree cone theory. Attempts to fasten appropriate anchor bolts in hard rock did not give satisfactory test results, so none of the towers have such footings. The selection of the type and dimensions of footing for a given location depended on examinations of the character of the site as excavation was in progress.

A typical footing for a single circuit suspension tower is 7 feet deep and has a diameter at the base of 4 feet. The reinforcing steel and the footing stub were put together and tack welded, so as to constitute one complete unit that could be placed in the holes and held in place by the template. Steel forms were used for the concrete, and in many cases were designed to be adjustable as to depth. The aggregate was ob-

Fig. 15 (below). Standard single circuit suspension tower

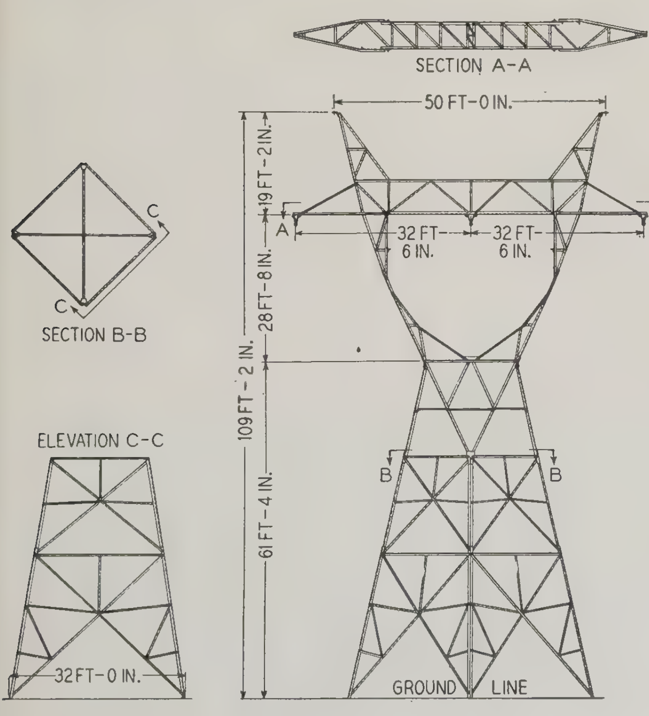
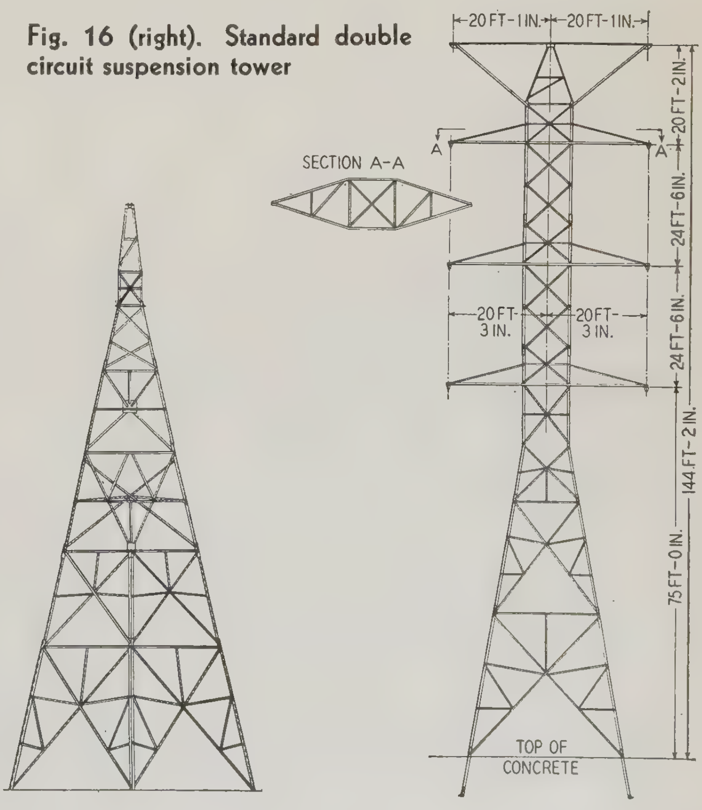


Fig. 16 (right). Standard double circuit suspension tower



tained from several favorable locations along the line. The quality of the concrete was maintained by checks on sample test pieces. A waterproofing compound was applied to the concrete preliminary to backfill.

Tower Location

Selection of right of way for this line was facilitated considerably by aerial observation and aerial mapping, which together with field observation made an accurate ground work upon which to proceed with the running of center lines and profiles.

In anticipation of the large amount of span, sag, and tension data that would be necessary for stringing the conductors and laying out the line on the profiles, an improved method of calculation was devised that was entirely analytical, adhered to catenary formulas, and readily could be reduced to a calculation form. For most of the tower locations a template was used that gave the center span sags for maximum hot day conditions for various spans. Within the ordinary span lengths, this curve did not depart very far from the true complete catenary curve for any one span. When especially long spans were studied, special templates would be made for the precise condition. For the single circuit tower section spans were held as near 1,000 feet as was desirable with due consideration to the topography.

Office analysis and layout was followed by a field check to verify that such a location and tower height

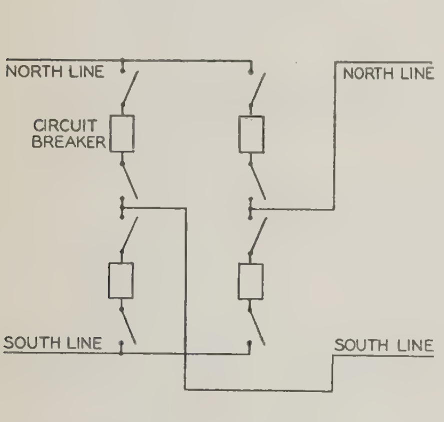


Fig. 17. One line diagram of intermediate switching station

was satisfactory from the standpoint of footings, safety from erosion by cloudburst, satisfactory from the standpoint of wire clearances to the ground, and other factors. Preliminary recommendations would be made for footings, unequal leg extensions, excavations, and other features, or pertinent data would be brought back to the office for further economic study of such matters. After final locations were chosen, the footings would be located, and detailed elevations of the ground at each leg would be given so that a proper selection of footing stubs could be made. The judgment on footings would be rectified or confirmed as excavation progressed.

Switching Stations

As was mentioned in connection with the stability studies, 2 intermediate switching stations are used for line sectionalizing, so as to switch out faulted line sections with the least possible disturbance to the continuity of power flow. These stations are located at almost exact $^1/_3$ points. The arrangement of oil circuit breakers and disconnecting switches is indicated in figure 17. This arrangement gives the required amount of flexibility for switching and maintenance with a minimum number of circuit breakers.

Switching stations are of the conventional outdoor, latticed column and girder type, occupying an area of 550x580 feet. The busses are supported with strain and suspension insulator strings and are constructed of cable similar to that used for the line.

Of special interest in these stations are the recently developed high speed impulse type of circuit breakers, the first and largest of their type ever built for commercial purposes.[23] Each breaker is rated at 287 kv, 1,200 amperes, and will interrupt up to 5,000 amperes. The over-all time of breaker action from energizing trip to extinguishing of the arc is not more than 3 cycles. The breakers have 8 contacts in series, housed within tubular horizontal members. These contacts are operated by springs, which are wound up by a motor driven mechanism; when the breaker is open the springs automatically are put in position to take care of the next closing and opening cycle. The extinguishing of the arc is accomplished by forcing a jet of oil across each contact at a pressure of 100 pounds per square inch.

As installed, the switch will be 27 feet high and will occupy a space of 22x54 feet. The amount of oil required is only 2,600 gallons for a complete 3 pole switch, of which only 210 gallons is exposed to arcing.

Although this circuit breaker constitutes a radically new development, every feature of its operation has been investigated and tested to the satisfaction of all parties concerned, such tests including 60 cycle and impulse voltage flashover, interrupting capacity, voltage distribution while opening, and mechanical life. On each side of the circuit breakers, motor-operated vertical-break disconnecting switches are installed.

For lightning protection, the station framework and all equipment are connected to a ground mat that is an extension of the counterpoise system. The overhead ground wires do not connect to the station framework, but are carried to isolated towers connected to the counterpoise system. These towers are 150 feet high and support the ground wires sufficiently high above the station to shield the structure from direct strokes.

Receiving Stations

Figure 18 shows a perspective sketch of receiving station *B*, the terminal of the Boulder Dam line. The station occupies an area of 1,600 x 677 feet. The central structure is the 132 kv switch rack, while the 4 similar structures at the 4 corners are the 33 kv racks. The operating room, repair shops, station auxiliaries, and storage rooms are housed within the concrete building in the foreground. Adjacent to the 132 kv rack are 2 banks of autotransformers, each bank of which is connected directly to a transmission

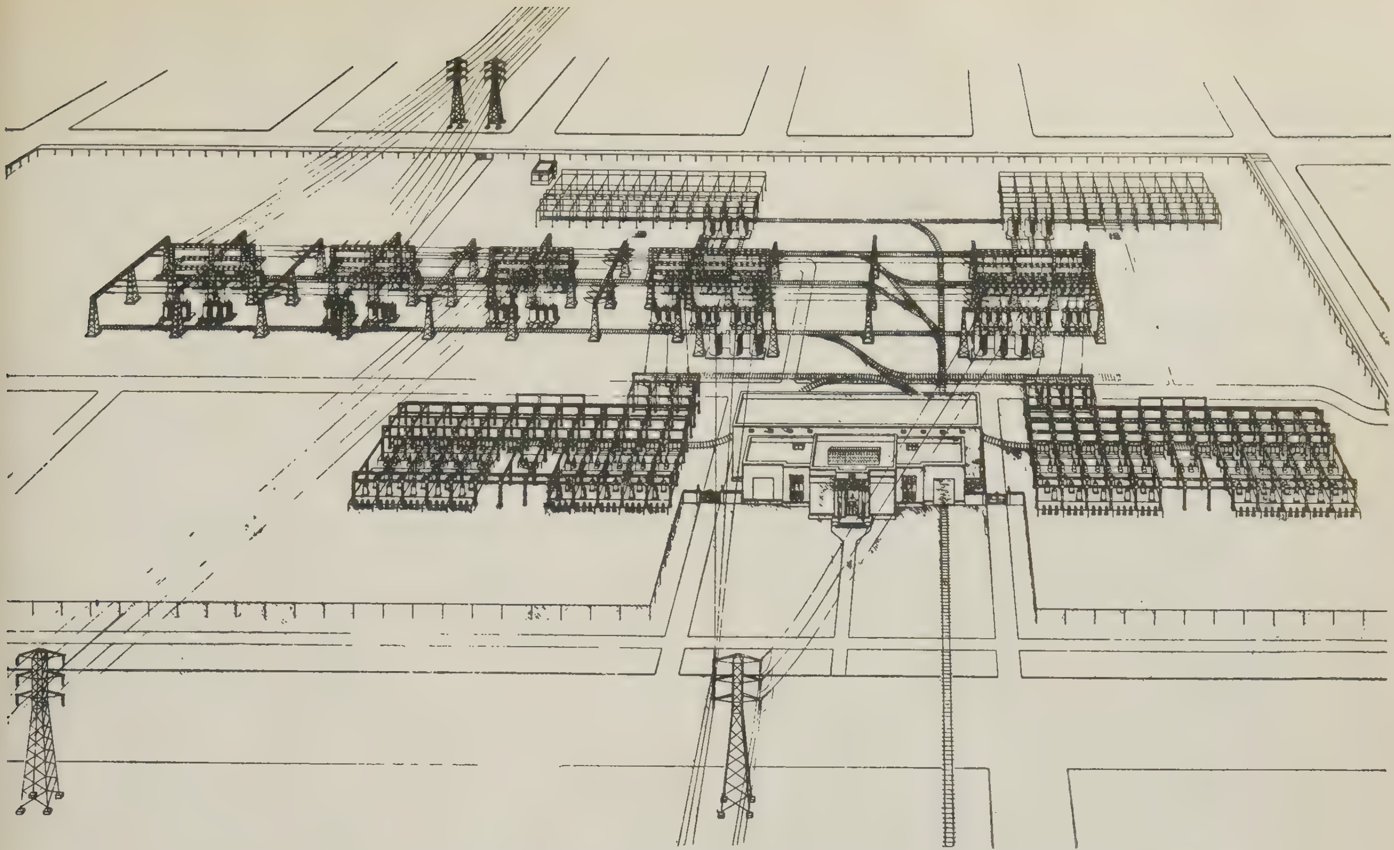


Fig. 18. Receiving Station B of the Los Angeles Bureau of Power and Light, terminal of the Boulder Dam Lines

circuit and serves to transform the voltage to 132 kv, thus eliminating the use of 287 kv circuit breakers at this station. Under the system of operation proposed for the lines, each of these transformer banks was required to have a self-cooled capacity under normal conditions of 120,000 kw. After carrying that load continuously, they were required to be capable of carrying 240,000 kw for 2 hours using forced air cooling when the other receiving end line section was out. They also had to be capable of carrying 150,000 kw continuously with forced air cooling to provide for the emergency rating of the line. In meeting these requirements, the actual ratings obtained for each single phase autotransformer were: 48,750 kw without blowers, 65,000 kw continuous with blowers, 80,000 kw for 2 hours with blowers. A 13,200 volt tertiary winding of 16,000 kva is provided for delta connection for circulating exciting current harmonics. These transformers have an impedance of 8.4 per cent at 65,000 kva, which is the lowest practicable impedance for the voltages involved. At this same load they have an efficiency of 99.47 per cent and a normal exciting current of 2.75 per cent. They are the largest autotransformers ever built to date.

Since these autotransformers are operated as parts of the lines, and their continuity of service is highly important, they will be protected on the 275 kv side with autovalve lightning arresters, which so far are the highest voltage arresters ever furnished commercially.

These autotransformers are connected to the 132 kv bus by means of 4 138-kv 1,200-ampere oil circuit breakers of the impulse type having the same speed and interrupting capacity as the circuit breakers in the switching stations. Four series breaks per pole are used at this lower voltage. The remaining 132 kv oil circuit breakers, which operate on the various double-circuit belt-line interconnections to 3 other receiving stations and on the 132/34.5 kv transformer banks, are of the conventional tank type and have a speed of 5 cycles and an interrupting capacity of 2,500,000 kva. Each of the 33 kv bus sections is supplied by a bank of 3 winding transformers. The bank rating on the secondary or 34.5 kv winding is 80,000 kva, which load is approximately at 0.75 to 0.80 power factor. The tertiary windings have a rating of 60,000 kva at 13,200 volts and are designed to be connected to the synchronous condensers, which furnish correction so that the primary windings operate at or near unity power factor with a rating of 60,000 kva. These transformer banks are connected star-star with a delta tertiary connection. At 70,000 kva these transformers have a primary to secondary impedance of 10.8 per cent. They have an efficiency at full load of 98.82 per cent.

For the initial installation, only 2 33 kv bus sections will be placed in operation at this point. A pair of "belt" transmission lines to station *D* will serve to extend the 132 kv bus to that similar receiving station, which will have 2 more similar transformer banks.

Full final details regarding the synchronous condenser installation cannot be given at this time, as they are dependent on stand-by steam plant arrange-

ments which still are being studied. A typical synchronous condenser will be of the hydrogen-cooled outdoor type and will have a rating of 60,000 kva leading, 36,000 kva lagging, at 600 rpm and 13,200 volts.

Relay and Communication System

Carrier frequencies will be imposed on the line for 4 distinct purposes: relaying, supervisory control of switching stations, telephone communication between stations, and telephone communication to patrolmen's automobiles in the vicinity of the line.

The carrier current relay system is of the lockout type. When given a fault signal from a ground relay or an overcurrent relay, directional element relays will check the direction of power flow. If the direction is normal at the 2 ends of a phase conductor of the circuit, a lockout action will prevent the switches on that section from tripping. Suitable filters are provided in the lines on each side of the station to isolate the various frequencies. The time of operation of this relay system is less than 3 cycles.

In addition to the carrier relaying system, conventional cross-balanced relays will be used, in which the current in a given phase of one circuit is balanced against the similar current in the other circuit at a given station. For most troubles, this relay system will be slightly more rapid than the other, except where the fault is near a station and cascade action of switching takes place.

Telephone communication will be provided over a separate wired line as well as over the carrier system. Patrolmen's cars will be provided with radio receiving sets tuned to the carrier frequency so that they can be given instructions when on the transmission line road, which is in the vicinity of the line for its entire length.

Conclusion

It is believed that this line not only has established a new voltage step in the transmission of electric power on the North American continent, but also has served to stimulate advances in the art and science of electric power transmission and related electrical fields. It is a milestone of current progress. In a project of this magnitude, it is unavoidable, or perhaps incidental, that many features are notable for their size, or capacity; but the ideal of the designers will have been realized if the system delivers the required power with the reliability and continuity of service that it seems reasonable at this time to expect.

Appendix—Statistical Data of Boulder Dam-Los Angeles Transmission System

Line

Number of 3-phase 60-cycle circuits	2
Line-to-line kilovolts, receiving end	275
Line-to-line kilovolts, sending end	287.5
Reliable operating capacity, kilowatts	235,000–240,000
Emergency capacity, kilowatts	300,000
Approximate full load loss, including transformers and synchronous condensers, per cent	8
Length of single circuit tower section, miles	225.3
Length of double circuit tower section, miles	40.8
Total length of double circuit line, miles	266.1
Length of sending end section, miles	91.7
Length of middle section, miles	90.8
Length of single circuit tower portion of receiving end section, miles	42.8
Length of double circuit tower portion of receiving end section, miles	40.8

Conductor

Diameter, inches		1.40
Type		segmental hollow copper
Total circular mils		512,000
Number of segments		10
Spiral pitch, inches		28
Weight per foot, pounds		1.57
Ultimate strength, pounds		21,600
Single circuit	Maximum line tension, pounds	8,700
	Normal tension at 60 degrees Fahrenheit, pounds	4,370
Double circuit	Maximum line tension, pounds	6,400
	Normal tension at 60 degrees Fahrenheit, pounds	4,750
Splice		Bronze sleeve with double wedge grip
Installation		Pulling in under tension controlled by 8 foot capstan and brake
Total pounds used, approximately		13,455,000

Overhead Ground Wire

Number per tower line		2
Single circuit towers	Material	1/2 inch galvanized steel, stranded
	Weight per foot, pounds	0.517
	Ultimate strength, pounds	18,800
	Maximum tension	5,000
	Normal tension	1,800
	Total pounds used, approximately	2,461,000
Double circuit towers	Material	0.4395 inch copper covered steel, stranded
	Weight per foot, pounds	0.421
	Ultimate strength, pounds	18,500
	Maximum tension, pounds	2,500
	Normal tension, pounds	1,600
	Total pounds used, approximately	181,000
Counterpoise	Material	1/4 inch rolled black copper rod
	Weight per foot, pounds	0.205
	Total pounds used, approximate	1,300,000
	Depth, feet	not more than 3
	Method of installation	by plow
	Method of attachment	4 spark gaps per tower

Span

Single circuit towers	Normal span, feet	1,000
	Average span, feet	984
	Maximum span, feet	1,811
	Minimum span, feet	431
	Normal sag, feet (1,000 foot span)	45
	Sag at 150 degrees Fahrenheit, feet (1,000 foot span)	48.5
Double circuit towers	Normal span, feet	850
	Average span, feet	839
	Maximum span, feet	1,620
	Minimum span, feet	331
	Normal sag, feet (850 foot span)	30
	Sag at 130 degrees Fahrenheit, feet (850 foot span)	33.5

Insulation

Light duty suspension unit	Size, inches	10 x 5*
	Strength, pounds	11,000
Heavier duty suspension unit	Size, inches	10 1/2 x 6*
	Strength, pounds	15,000
Standard suspension insulator string		24–(10 x 5)
Standard angle suspension insulator string		22–(10 1/2 x 6)
Heavy duty strain insulator string		double 22–(10 1/2 x 6)
Light duty strain insulator string		double 26–(10 x 5)

* Diameter of unit by spacing between units.

Clearances

Up to 4 pounds per square foot wind, feet	11
At 12 pounds per square foot wind, feet	7
Suspension horn arcing distance, inches	110
Angle suspension arcing horn distance, inches	121
Heavy duty strain arcing horn distance, inches, approximate	117
Light duty strain arcing horn distance, inches, approximate	115
Minimum vertical distance to surface of ground:	
desert and mountain sections, 150 degrees Fahrenheit, feet	27†
coastal plain section, 130 degrees Fahrenheit, feet	45‡

† Some inaccessible locations 22.5 feet.
‡ Some nonagricultural hilly locations 40 feet.

Hardware

Conductor	Strain clamp	Bronze sleeve, double wedge grip
	Suspension clamp	Free center, double saddle type
	Lower arcing horn	Figure "8"—$1^1/_4$ inch pipe
	Upper arcing horn	Steel strap—$^3/_8$ x $1^1/_2$ inches
	Strain string arcing horns	$1^1/_4$ inch pipe ovals above yokes
	Yokes, low frequency vibration	21 inch string spacing
Ground wire	Strain clamp	Special 315 degree snubbing type
	Suspension clamp	Standard trunnion type

Single Circuit Towers

Loading		$^1/_2$ inch ice, 8 pounds per square foot wind
Suspension type	Broken wire assumptions	1 conductor, 1 ground wire
	Conductor spacing, feet	32.5
	Crossarm height, standard tower, feet	90
	Ground wire spacing, feet	50
	Ground wire height, standard tower, feet	109
	Extensions, feet	10, 20, 30, 40
	Tower base, feet	32 x 32
	Weight, pounds	18,100
Angle suspension	Broken wire assumptions	3 conductors, 2 ground wires
	Horizontal line angles, degrees	0 to 10
	Weight of 10 degree tower, pounds	25,400
Strain type	Broken wire assumptions	3 conductors, 2 ground wires
	Horizontal line angles, degrees	0 to 50
	Weight of 50 degree tower, pounds	27,925

Double Circuit Towers

Loading		no ice, 12 pounds per square foot wind
Suspension type	Broken wire assumptions	1 conductor, 1 ground wire
	Conductor spacing: Vertical, feet	24.5
	Conductor spacing: Horizontal, feet	40.5
	Lower crossarm height, standard tower, feet	75
	Ground wire spacing, feet	40.5
	Ground wire height, standard tower, feet	144
	Extensions, feet	10, 20, 30, 40
	Tower base, feet	32 x 32
	Weight, pounds	23,050
Angle suspension	Broken wire assumptions	3 conductors, 2 ground wires
	Horizontal line angles, degrees	0 to 10
	Weight of 10 degree tower, pounds	38,300
Strain type	Broken wire assumptions	6 conductors, 2 ground wires
	Horizontal line angles, degrees	0 to 90
	Weight of 50 degree tower, pounds	41,150

Standard Footings

Type		reinforced concrete, pad and pedestal
Diameter and depth	Single circuit suspension tower, feet	4 x 7
	Single circuit 10 degree angle tower, feet	5 x 7 (side); 6.5 x 9.5 (long)
	Single circuit 50 degree strain tower, feet	7 x 9.5
	Double circuit suspension tower, feet	4.25 x 8
	Double circuit 10 degree angle tower, feet	7 x 10.5*
	Double circuit 50 degree strain tower, feet	8.5 x 12*

* Preliminary and approximate.

Generators

Number used on 2 circuits	4
Kilovolt amperes each at unity power factor	82,500
Voltage	13,800/16,500
Number of poles	40
Speed, revolutions per minute	150/180
Short circuit ratio	2.28/2.74
Direct axis transient reactance, per cent	21/17.5
Moment of inertia (WR^2) each	not less than 105,000,000
Total weight, pounds, approximate	2,000,000
Outside diameter, feet	40
Type of insulation	Class *B*
Excitation	nominal 250 volts, main and pilot exciter direct connected
Exciter response	0.50

Sending End Transformers

Number used on 2 circuits (2 banks)	6
Type	Water cooled, outdoor
Rating of each, kilovoltamperes	55,000
Voltage	287,500Y/16,320 delta
Frequency, cycles per second	60
Impedance, per cent	not more than 10.73
Exciting current at normal voltage, per cent	4.5
Full load efficiency, per cent	99.31
Three-quarter load efficiency, per cent	99.33
Total weight per unit, pounds	385,000
Floor space and height, feet	13 x 20 x 32

Receiving End Autotransformers

Number used on 2 circuits	6
Type	forced air cooled
Rating of each, kilovoltamperes	48,750, no blowers; 65,000, blowers; 80,000, 2 hours, blowers
Tertiary winding rating, kilovoltamperes	16,000
Voltage	275,000Y/132,000Y/13,200
Frequency	60
Impedance, primary to secondary, per cent on 65,000 kilovoltamperes	8.4
Exciting current at normal voltage, per cent	2.75
Full load efficiency at 48,750 kva, per cent	99.487
Full load efficiency at 65,000 kva, per cent	99.466
Full load efficiency at 80,000 kva, per cent	99.422
Total weight per unit, pounds	332,000
Floor space and height, feet	$11^1/_2$ x $23^1/_2$ x 36

Three Winding Transformers

Number used for 2 circuits		12
Type		forced air cooled outdoor type
Kilovoltamperes each		primary 60,000, secondary 80,000, tertiary 60,000
Voltage		76,200/20,000/13,200 delta (132,200Y/34,500Y/13,200)
Frequency, cycles per second		60
Impedance	Primary to secondary (23,333 kva), per cent	10.8
	Primary to tertiary	12.3
	Secondary to tertiary	3.3
Exciting current, normal voltage, per cent		2.75
Full load efficiency, per cent		98.988

Synchronous Condensers

Kilovoltamperes, each	60,000 lead/36,000 lag
Voltage	13,200
Number of poles	12
Speed in revolutions per minute	600
Direct axis transient reactance, per cent	45
Moment of inertia (WR^2) each, pound-feet^2	1,250,000
Type of insulation	Class *B*
Excitation	motor generator, main and pilot exciter, 250 volts
Exciter response	0.5

Oil Circuit Breakers for Switching Stations

Type	porcelain clad, impulse
Voltage class, kilovolts	287.5
Interrupting capacity, kilovoltamperes	2,500,000
Normal current rating, amperes	1,200
Speed of operation, cycles	3
Weight, pounds	113,300
Floor space and height, feet	22 x 54 x 27
Gallons of oil	2,600

Oil Circuit Breakers for Receiving Stations

Type	porcelain clad, impulse
Voltage class, kilovolts	138
Interrupting capacity, kilovoltamperes	2,500,000
Normal current rating, amperes	1,200
Speed of operation, cycles	3
Weight, pounds	51,000

Floor space and height, feet . . . 20 x 22 x 22
Gallons of oil . . . 750

Oil Circuit Breakers for Receiving Stations

Type . . . tank
Voltage class, kilovolts . . . 138
Interrupting capacity, kilovoltamperes . . . 2,500,000 (convertible to 4,000,000)
Normal current rating, amperes . . . 1,200
Speed of operation, cycles . . . 5
Weight, pounds . . . 100,000
Floor space and height, feet . . . 8 x 26 x 17
Gallons of oil . . . 7,380

Lightning Arresters

Voltage class, kilovolts . . . 287.5
Kilovolts, line to ground . . . 235.0
Mounting . . . suspension
Crest voltage at 1,500 ampere discharge, kilovolts . . . 825
Impulse voltage breakdown, kilovolts . . . 800
Over-all height, feet . . . 33

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Time-Temperature Tests to Determine Machine Losses

Time-temperature tests as a means of measuring losses in electrical machines are described in this paper, and some of the results which have been secured with such tests are described. The method consists principally in determining by test the initial slope of the time-temperature curve of some part of the machine, immediately after a steady load is thrown off. In this paper, application to the analysis of losses in turbine generators is described, although the method can be applied to other electrical apparatus.

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In the early days of the electrical industry the design of electrical machines was largely a matter of rule of thumb and progress was made through the trial and error method. As designers worked out the underlying theory of machine performance the apparatus produced soon took on general forms which have existed with little fundamental change to the present day. Calculation of the losses in machines has, within the past 10 years, reached a point where most of them can be estimated in advance of the tests with very good accuracy. Most of these calculations, however, still involved the judicious use of empirical factors depending upon the machine proportions, materials, etc. Load losses in machines still presented a considerable problem as they were made up of a number of losses whose distributions were little known.

It will, therefore, be seen that the machine designer, while having very useful tools in these calculation methods, had no means of checking the distribution and location of the losses throughout the various parts of the machine by actual test. An accurate knowledge of their distribution was essential if further refinements in design were to be made. In 1926, certain preliminary tests were made by C. M. Laffoon and J. F. Calvert[1] to determine the feasi-

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1. For all numbered references see list at end of paper.

bility of measuring the rate of heat input to various parts of a turbine generator. They indicated that a new tool in the form of time-temperature tests was available to the designer to examine more closely the location of various losses and their causes. Since that time a notable contribution to this subject was made in an article by Prof. S. Parker Smith.[2]

The present paper covers the work carried on by one manufacturer in analyzing losses in turbine generators. The method, however, is not limited to such machines only, but can be applied to many lines of electrical apparatus.

General Theory of Time-Temperature Tests

Briefly, the method of determining losses by time-temperature tests is to bring the machine under test up to constant temperature at the load condition to be checked. The load is then suddenly thrown off, reducing the electrical losses to zero. If the cooling system is not changed during the test the initial slope of the time-temperature curve after throwing off the load will be a measure of the heat input to the part under consideration.

Assume

q_i = the rate of heat flow into the part
q_c = the rate of heat flow to the cooling medium
θ = temperature of the part under test
θ_0 = temperature of the part previous to dropping the load
θ_c = temperature of the cooling medium
t = time
c = specific heat of the material
k = thermal conductivity of heat path to the cooling medium

Assume the part under consideration consists of a homogeneous material with uniform loss generated in it. The heat balance equation for this part at any time may be represented by the following equation:

$$q_i = q_c + c\frac{d\theta}{dt} = k(\theta - \theta_c) + c\frac{d\theta}{dt} \qquad (1)$$

where the factor $c\dfrac{d\theta}{dt}$ represents the rate at which heat is stored in the material.

With the machine at steady temperature under load, $c\dfrac{d\theta}{dt} = 0$. At the instant that the load is dumped the heat input q_i becomes zero. To maintain the heat balance, the following must hold true:

$$c\frac{d\theta}{dt} = -q_c = -k(\theta - \theta_c) \qquad (2)$$

From this the equation of the time temperature curve is:

$$\theta = \theta_c + (\theta_0 - \theta_c)\epsilon^{-\frac{k}{c}t} \qquad (3)$$

The slope of this curve at time $t = 0$ (when the load is dropped) is:

$$-\frac{d\theta}{dt} = \frac{k(\theta_0 - \theta_c)}{c} = \frac{q_i}{c}$$

Therefore,

$$q_i = -c\frac{d\theta}{dt} \qquad (4)$$

Before throwing off the load the heat input q_i equals the heat dissipated through the cooling system. When q_i becomes zero, the temperature of the material begins to fall at such a rate that, for a short time, the heat flowing to the cooling system does not change. It is, therefore, only necessary to determine this slope accurately by test and apply the proper specific heat value in equation 4 to obtain the heat input to the part under consideration.

It will be noted that the material under consideration was assumed to be of a homogeneous nature. Many materials encountered in machines are not of this type, and it is necessary in that case to obtain an equivalent specific heat value by testing a sample or the part itself with a known heat input and determining the slope of the time-temperature curve with this known loss. The second assumption made was that the loss was generated uniformly throughout the material. Analysis of this problem will disclose that equation 4 still holds true, the heat transfer in the material itself during the cooling down period only affecting the shape of the time-temperature curve some time after the load is dropped. The losses are usually generated in electrical machines with sufficient uniformity that these transients due to unequal distribution do not materially affect the first 5 minutes of the time-temperature curve.

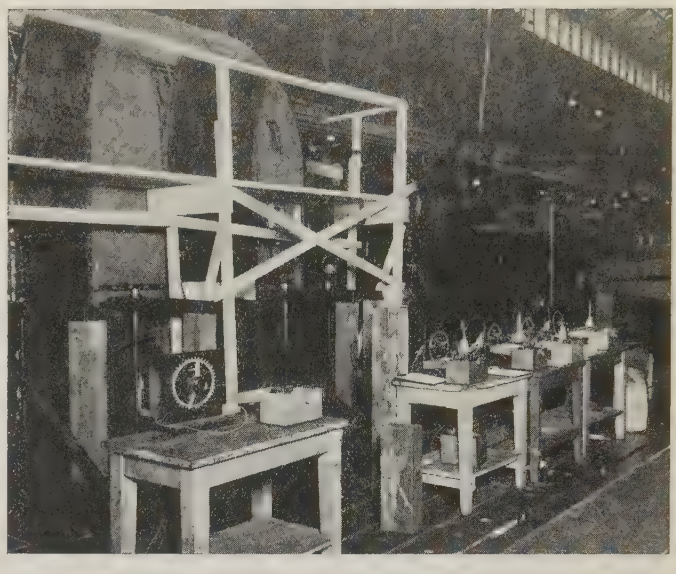

Fig. 1. Arrangements for testing 100,000 kva turbine generator. Potentiometers, dial switches, and thermocouple cold junctions in vacuum bottles are on tables in the foreground

Procedure in Testing A-C Machines

In testing a turbine generator to determine the distribution of the electrical losses, thermocouples are soldered to the parts of the stator whose losses are to be measured and leads are brought out to a potentiometer for measuring the temperature. The usual arrangement when a number of couples are to be used is to connect about 4 to 6 of them to a dial switch

and from the switch to the potentiometer so that one operator can read the temperatures of a number of couples. The cold junction for the group is immersed in a vacuum bottle, which is maintained at constant temperature during the test. Several such meters may be required to read all the thermocouples installed in the machine. Figure 1 shows the arrangement of temperature measuring equipment for testing a 100,000 kva generator. The machine to be tested is arranged to be driven by a direct connected motor so that the ventilation will not change when load is thrown off. The machine is held on load until constant temperatures are reached. The field switch is then opened. If the machine is operating at zero per cent power factor in parallel with another machine, the main circuit breaker is opened before opening the field switch. Readings of temperature and time are then taken for each couple over a 20 minute period. A typical time-temperature curve of a thermocouple embedded in the stator laminations is shown in figure 2. As it is important to obtain as large a number of accurate readings as possible in the 20 minute period, 2 readers are used to each potentiometer, one to read the potentiometer and the other to record the time and the temperature readings.

All tests were made with the usual low range portable potentiometers, which could be operated quickly but left something to be desired in accuracy in measuring low loss densities, as it is desirable to determine the temperature readings with an accuracy of better than ±0.1 degree centigrade when the initial slope of the curve is below 0.5 degree centigrade per minute. The accuracy obtained seemed to be of the order of ±0.2 degree centigrade. For rates of temperature change exceeding 0.5 degree centigrade per minute, the portable potentiometer has satisfactory accuracy. As the tests described here were not intended to be made with laboratory precision, the equipment used gave sufficiently accurate results for design purposes.

Measurement of Losses in Armature Coils

In one case thermocouples were built into an armature coil connected to the neutral of the star winding so that losses could be measured at a number of points in the coil. While very satisfactory results were obtained by this method, it is not applicable to most cases as it is undesirable to install such couples on account of the necessity of removing the coil from the machine after test. A method of measuring the total loss in the armature copper, including both the so-called d-c loss and eddy current losses, was, therefore, worked out as follows. Direct current was circulated through the armature winding with the rotor at standstill until the temperature of the winding became constant. The d-c supply circuit was then opened and a time-temperature curve of the stator winding was obtained by measuring the stator temperatures by resistance of the windings. The apparent specific heat of armature windings was found to be 1.7 to 2.1 times the theoretical value for copper. With the machine running under load, arrangements were made as shown in figure 3 to measure the winding resistance as soon as the load was dropped. It was found necessary to use a filter circuit, to reduce the a-c current in the circuit generated by the residual magnetic field of the rotor. The filter shown in figure 3 was made up of a standard potential transformer and a condenser which happened to be available at the time tests were made. A low value of d-c current was circulated through the windings when taking temperature readings after dropping the load and the voltage drop across the winding measured, in preference to the use of a wheatstone bridge, as it was found that more consistent readings could be obtained by the volt-ampere method. The initial slope of the time-temperature curve of the armature winding was a measure of the total loss of the armature coil and this could be determined accurately using the specific heat value obtained by the calibration test.

Calibration Tests on Steel Materials

Time-temperature tests were made on ring samples of armature laminations and solid iron rings to determine the proper specific heat values to be used in calculating the loss values. The sample to be tested was connected to the usual core loss measurement apparatus and excited so as to obtain a certain loss in it. After the sample reached constant temperature the excitation was cut off and a time-temperature test was run. In testing the laminated material, thermocouples were soldered to a lamination at the middle of the ring sample. Thermocouples in the solid steel ring sample were peened into holes drilled in the material. The same method of attaching thermocouples to solid machine parts was carried out in all tests. The apparent specific heat value for a one inch square solid iron ring was 4.0 watt-minutes per pound per degree centigrade, which is only slightly higher than the theoretical specific heat of steel, but the apparent specific heat value for the 0.014 inch thick laminated material was found to be 4.55 watt-minutes per pound per degree centigrade, which is 30 per cent higher than that of steel. This difference in specific heat value is believed due to the

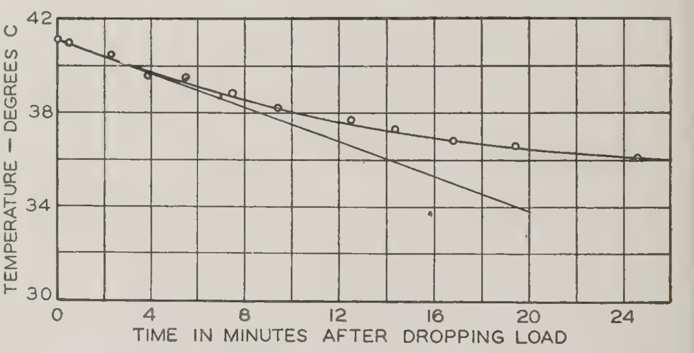

Fig. 2. Typical time-temperature curve taken with a thermocouple embedded in a tooth in the stator core. Initial slope of the curve equals 0.365 degrees centigrade per minute. Watts loss per pound equals 1.65

thermal lag of the thermocouple with regard to the iron temperature. This difference in specific heat value was also noted in Professor Smith's article. Losses set up at machine frequency or higher in solid iron parts are confined to a thin skin on the outside of the material due to the well-known "skin effect." Analysis of the heat flow due to this unequal distribution of losses indicated that the transients due to distribution of the heat throughout the material would be very rapid when the thickness of the steel did not exceed an inch—a common material thickness used in machines. The specific heat value obtained with the one inch square sample of steel was, therefore, considered to be representative of most cases encountered in machines, and the loss was figured on the basis of the total weight of material involved rather than that of the outer skin, which was of unknown extent.

Measurement of Rotor Surface Losses

So far only losses measured in the stationary parts have been under discussion. An attempt was made to measure the losses on the surface of the rotor of one machine by means of thermocouples embedded there and brought out through holes in the shaft to slip rings. The readings obtained were somewhat erratic due to variations in the resistance of the current collecting mechanism and to induced a-c currents in the thermocouple wiring, which were sufficiently rectified in some of the points in the circuit to affect the d-c voltage at the potentiometer. This rectification of stray a-c currents was first noticed when attempts were made to measure stator losses by throwing on load rather than throwing it off as later adopted. Sufficient stray fields existed, with the load on, to cause erratic temperature readings. The practice of bringing the machine up to full temperature and then dropping the load was, therefore, adopted, with a marked improvement in the consistency of temperature readings due to the absence of stray fields. So far as is known, no satisfactory method of measuring rotor temperatures with sufficient accuracy has been developed to determine losses in the steel parts.

Some Results of Tests

In all, 5 turbine generators ranging from 3,750 kva to 100,000 kva have been given time-temperature tests, from which valuable design information was obtained. With 3 of the 5 machines sufficient readings were taken to determine quite accurately the total stator loss, which was found by multiplying the weights of the various parts by their test loss per pound and summing up these losses. The stray losses in the rotor in these cases were known to be relatively small, from calculations made of these factors. The total stator losses checked quite closely with the values obtained by the usual segregated loss method as carried out in regular tests of a-c machines, which indicates that the method of testing was sufficiently accurate for the designer's purpose.

While it is impossible to go into detail here as to the findings of these tests, a few of the more important points might be of interest:

1. The losses in the laminated iron parts were found to be from 25 per cent to 80 per cent higher than the Epstein tests for the same material and the same flux density would indicate.

2. The losses in some of the frame parts in one case were found to be as high as 40 watts per pound at over-voltage. As a result of this information later machines have been designed with certain changes to eliminate most of these frame losses which appeared in the core loss.

3. The 100,000 kva generator mentioned above had a single conductor coil with strands transposed throughout the length of the embedded parts of the coil by the Roebel method to eliminate eddy currents. The calculated eddy factor for the coil using the usual formulas was 1.20. When tested, the eddy factor was found to be 2.0 instead of the calculated 1.2, or the eddy losses were 5 times higher than the calculated value. A check was then made to find where the extra loss was coming from. It was found that the coil (which was made in halves) had all its strands short-circuited at each end of each half coil and, while satisfactorily transposed to avoid extra losses due to cross flux in the embedded portions, was totally untransposed so far as fluxes in the end windings were concerned. A rough check of this factor, which is too complicated to lend itself to accurate analysis, indicated the possibility of obtaining such a high eddy factor due to this cause. A factor which had always been considered negligible was, therefore, found to be a very important one. As a result of this information a later machine of similar construction was connected at the ends of the half coils in a number of independent groups which were suitably transposed so as to eliminate almost entirely the extra losses due to end winding fluxes.

A filter made up of a potential transformer and condenser is used to shunt out alternating current due to residual magnetic field

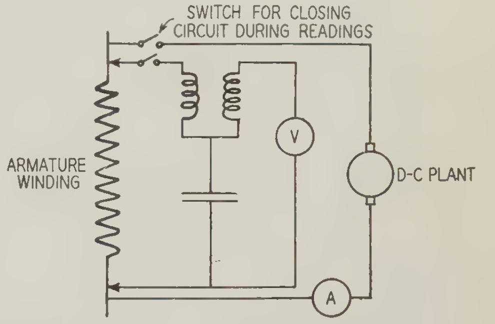

Fig. 3. Meter connections to measure resistance of stator windings by volt-ampere method

Attention to details of design such as mentioned here has been largely instrumental in the reduction in size and improvement of performance that is steadily going on in the design of turbine generators. The data obtained on turbine generators has been applied to other a-c machines resulting in improved performance, particularly in large a-c synchronous apparatus. As stated above, the use of time-temperature tests is not confined to the measurements of turbine generator losses, but can be applied profitably to solve a large number of electrical and mechanical problems where a sudden decrease of the losses may be obtained and the ventilation can be maintained constant throughout the test.

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2. Report on a 3-Phase Turbo-Alternator, Prof. S. Parker Smith. *The Engineer* (British), v. 145, Apr. 6, 1928, p. 366–8; Apr. 13, 1928, p. 402–4.

Storage Battery Charging

The fundamental reactions in accordance with the generally accepted "double-sulphate" theory of storage battery charging are comparatively simple. Additional reactions and phenomena, such as gas evolution, acid concentration, heating, and local action are factors which affect charging conditions. Data showing the effects of these factors are given in this paper. The ampere-hour law regarding charging rates is illustrated. Results of constant voltage and modified constant voltage charging are given, and constant voltage floating and trickle charging are discussed. Various means of automatic control for charging batteries in different classes of service are given, some of these schemes involving the use of ampere-hour meters and voltage relays.

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WHILE the reactions which take place during the charge and discharge of the lead-acid storage cell are not in all respects fully understood and have been the subject of some controversy, the fundamental facts, in so far as they affect the practical industrial application and control of the storage battery, are well established and may be recapitulated briefly here as a foundation for the discussion of storage battery charging to follow.

In view of the more recent investigations on the subject there appears to be no good reason for questioning the so-called "double sulphate" theory originally advanced by Gladstone and Tribe as expressed in the following equation:

$$PbO_2 + 2H_2SO_4 + Pb \rightleftarrows PbSO_4 + 2H_2O + PbSO_4$$

the left hand member representing the charged condition and the right hand member the discharged condition. This equation presents the initial and final condition of such parts of the active material and the electrolyte as are involved in the reactions.

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In both positive and negative plates there must necessarily be an excess of active material over that theoretically required and a similar surplus of electrolyte must also be present.

It will be observed from the above equation that during discharge a part of the sulphuric acid in the electrolyte is combined with the active material, forming lead suphate in both positive and negative plates, while a corresponding amount of water is produced, giving rise to the well-known reduction in the specific gravity of the electrolyte during discharge and the corresponding increase during the charge.

Up to this point the charging of a storage battery appears to be a very simple matter consisting merely in passing current through the cell in the charging direction until all the active material has been restored to full charge condition. In fact, during the early commercial development of the storage battery very little was done in the matter of a comprehensive study of storage battery charging. There are, however, several other phenomena and conditions which develop during the charge which are not indicated by the fundamental formula, which will now be briefly discussed.

Acid Concentration in the Plates

A further study of the reactions indicated by the fundamental equation given above will show that during the charge strong sulphuric acid is formed in the active material of both plates, the sulphate radical (SO_4) dissociated from the lead combining with the hydrogen from the water present, whose oxygen, (part of which is transferred by ionic migration from the negative to the positive plate) combines with the lead of the positive plate to form lead peroxide (PbO_2). This gives rise to a higher concentration of acid in the pores of the plates than that of the free electrolyte outside, on account of the time required for diffusion. Diffusion takes place more readily near the surface so that the acid concentration is greater in the more inaccessible parts, producing higher counter electromotive force to oppose the charging current. These inaccessible regions charge more slowly, therefore, and are the last to be fully charged. The gradual rise of acid concentration produces gradual rise of voltage. The effect of high acid concentration in retarding the charge is more marked in the case of the negative plate and if the acid concentration is sufficiently high, it is impossible to reduce the sulphate to spongy lead.

Gassing

The conversion of the lead sulphate ($PbSO_4$) into lead peroxide (PbO_2) in the positive plate and lead in the negative plate is not the only reaction occurring while charging current is passing. These are the preferential reactions and take place so long as there is sufficient sulphated active material accessible to absorb the current, and diffusion can take place at a rate which will prevent excessive acid concentration in the pores of the plates. Whenever the charging current exceeds this value, the excess which cannot

be used for charging the active material causes decomposition of the water of the electrolyte into hydrogen and oxygen which are released as bubbles of gas—the hydrogen at the negative plate and the oxygen at the positive—and the familiar phenomenon of gassing appears. A higher voltage is required to release gas than to charge the active material so the beginning of active gassing is indicated by a comparatively rapid rise of voltage at the cell terminals. The accompanying diagram, figure 1, shows a typical charge curve and illustrates the phenomena just referred to, namely, the gradual rise of voltage during the early part of the charge caused by increased concentration of acid density and the rapid rise of voltage toward the end of the charge at the point where gassing begins, followed by a flattening of the curve when the cell is fully charged and all of the charging current is consumed in the evolution of gas, the conditions then becoming constant.

The rate of gas evolution is also shown on this curve, as well as the rise of specific gravity as the charge progresses. The more rapid rise of this specific gravity curve after gassing begins is the effect of the gas bubbles in forcing out the heavier electrolyte from the pores of the plates as well as the stirring up of heavier electrolyte which may have settled to the bottom of the cell.

Faraday's Law

According to Faraday's law a given amount of current passing through an electrolytic cell can produce only a definite amount of electrochemical reaction. Hence, that part of the current which produces gas by decomposing the water in the electrolyte cannot have any effect in charging the active material. This applies separately to the positives and

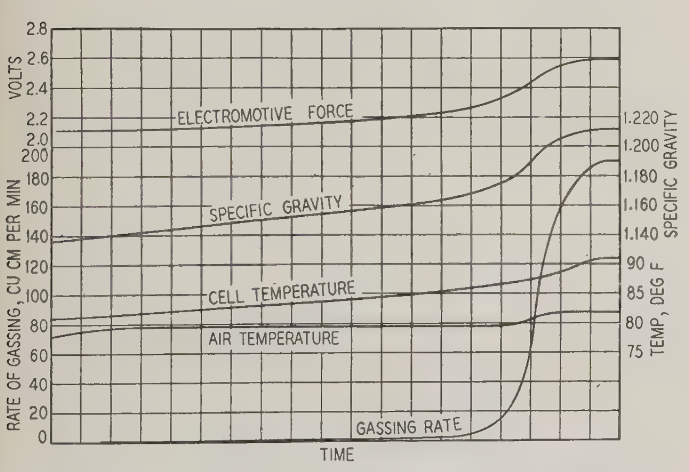


Fig. 1. Typical curves of charge voltage, specific gravity, and gassing. Charge at 8 hour discharge rate following 8 hour discharge

the negatives—that is, the same current which produces gas (oxygen) at the positive plate after that plate is fully charged may still be charging the active material of the negative plate if that plate is not fully charged, but any part of the charging current which produces gas at both plates is absolutely

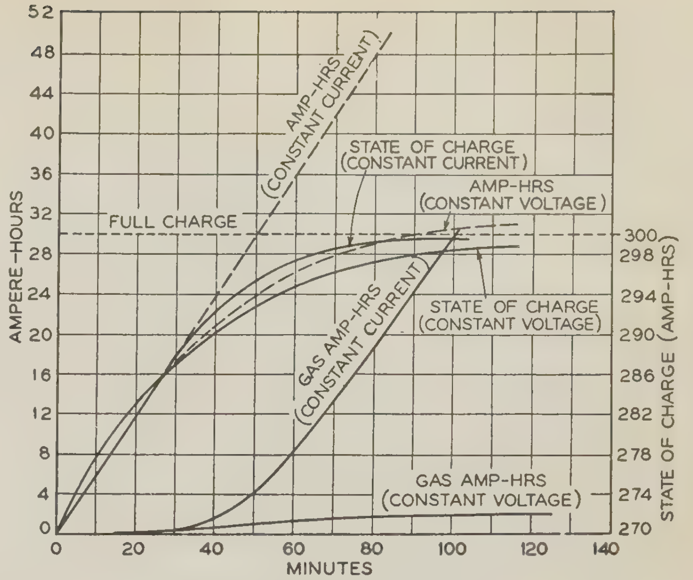


Fig. 2. Constant current versus constant voltage charge following one hour discharge at 10 hour rate (30 amperes)

Constant current = 36 amperes
Constant voltage = 2.25 volts per cell
Constant temperature = 26.5 degrees C

wasted as far as charging the active material is concerned.

The accompanying diagram, figure 2, illustrates this fact, showing the results of 2 charging tests following a 10 per cent discharge, in one of which the cell was charged at constant current and in the other at constant voltage. The rate of evolution of gas was measured in each case and converted into ampere-hours by well-known electrochemical constants, and plotted in the form of curves. The ampere-hours actually put into the cell are shown in dotted lines, and from this was subtracted the ampere-hour equivalent of the gas evolution, leaving the net ampere-hours used for charging the active material, indicated by the curves marked "state of charge." It will be noted that the constant voltage method, at 2.25 volts, charged the cell almost as rapidly as the constant current method, and much more efficiently. The next curve, figure 3, shows a similar test following a 20 per cent discharge.

Heating Effects

The heat produced in a cell during the charging period is due to 3 causes. First, there is the ordinary resistance loss (I^2R) determined by the current and the true ohmic resistance of the cell. The internal resistance of commercial storage battery cells is comparatively small so that unless abnormally high charging rates are used the temperature rise during the early stages of the charge is not excessive, notwithstanding the fact that the internal resistance of a discharged cell is somewhat greater than when fully charged.

The second cause of heat generation is that due to the sum of the normal chemical reactions. Also, the mingling of the sulphuric acid produced by the charging current with the water of the electrolyte

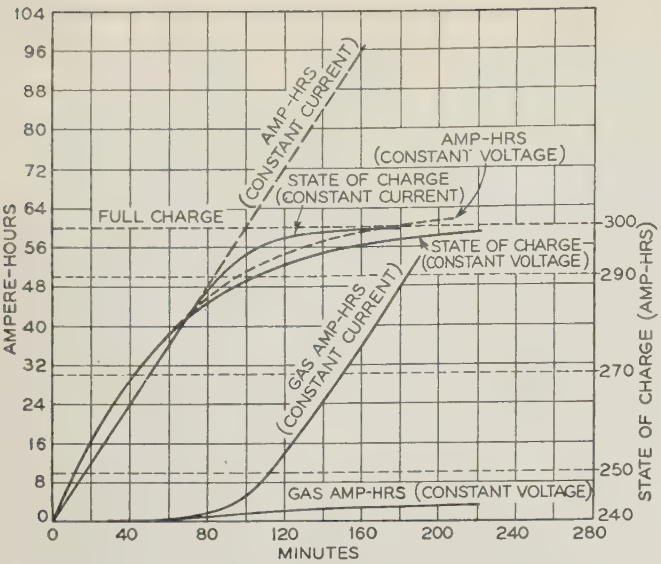


Fig. 3. Constant current versus constant voltage charge following 2 hour discharge at 10 hour rate (30 amperes)

Constant current = 36 amperes
Constant voltage = 2.25 volts per cell
Constant temperature = 25 degrees C

produces some heat. These heating effects are small and practically negligible under ordinary operating conditions.

Toward the end of charge another quantity of heat is developed, the source of which is somewhat obscure. The total energy represented by the product of the charging current by the final charge voltage is appreciably greater than the sum of the resistance loss and the electrochemical energy involved in the decomposition of the water of the electrolyte into oxygen and hydrogen. This difference appears in the form of heat. One of the theories advanced to account for this is the production of ozone at the positive plate as an intermediate reaction, which is immediately converted into oxygen with the development of heat. This theory is plausible, as the familiar odor of ozone is often noted. Another theory involves the formation of atomic hydrogen at the negative plate. It has thus far been impossible to establish these theories quantitatively. However, the rapid rise of temperature after gassing begins is a well-known fact.

Stratification

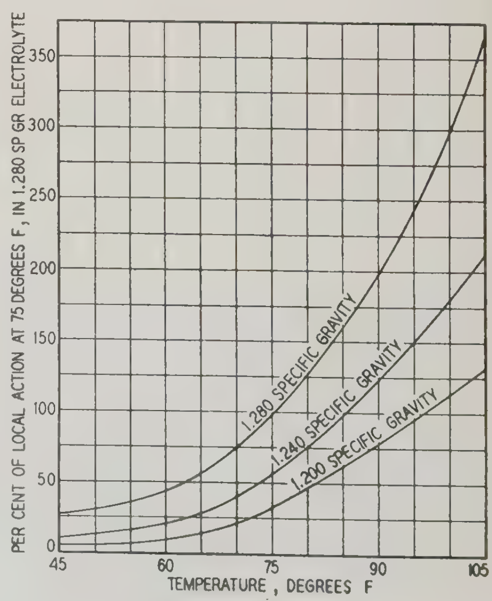
Stratification of the electrolyte is another phenomenon which may sometimes be observed. As already pointed out, concentrated sulphuric acid is produced in the pores of the plate by the charging current. In the early stages of a high rate charge this strong acid can be observed coming out of the plates and on account of its density sinking toward the bottom, during which process it mingles with the weaker acid between the plates. A small amount of this heavier electrolyte may settle into the region below the plates, but most of this will be stirred up by the convection currents produced by the gas bubbles during the later stages of the charge. In stationary cells the electrolyte in the dead space from the bottom of the cell to a point about $^3/_4$ inch to 1 inch below the bottoms of the plates will usually show a slightly higher density than that of the active electrolyte above this level, but when this increased density has reached a value equal to that of the heavier electrolyte which comes out of the plates during the charge after it has mingled with the weaker electrolyte between the plates, no further effect of this kind can occur.

The only result of stratification is a slight weakening of the active electrolyte which, while beneficial in respect to the life of the plates, will somewhat reduce the available capacity. This result will ordinarily be more than offset by the building up of the capacity of the plates in service. This phenomenon does not occur in batteries maintained by floating or trickle-charging, and any mechanical vibration or disturbance to which a battery is subjected will tend to minimize it.

Effect of Local Action

It is well recognized that a certain amount of local action or self discharge is taking place continually in a storage battery cell. By far the greater amount of this local action occurs in the negative plate. A full discussion of this subject would call for a separate treatise, but a few of its most important features may be mentioned as having a bearing on charging conditions. Local action takes place continuously, whether the battery is charging or discharging or standing on open circuit. It increases rapidly with increase of temperature and with increase in the specific gravity of the electrolyte. The accompanying curves, figure 4, will illustrate these effects. Local action is evidenced by the gassing of the negative plates when standing on open circuit. It results in the gradual sulphation of the negative material and the consequent falling off of the specific gravity of the electrolyte. It must be taken into account in determining the charging routine for a battery. Certain impurities in the electrolyte such

Fig. 4. Variation of local action with temperature and specific gravity of electrolyte



as platinum have a profound effect on this phenomenon. However, such impurities are unusual and it is not difficult to guard against this source of trouble. Cells which have been in service for a considerable length of time will usually exhibit some increase in the amount of local action. There also appears to be a quite definite relation between the amount of local action and the final voltage of the cell at the end of charge. The accompanying charge curves, figure 5, of 3 cells will illustrate this.

The 3 cells had been fully charged and then stood on open circuit for 5 days. They were then charged in series, and the charge voltage readings plotted as shown. The difference in the amount of local action is clearly indicated. In cell *A* the local action is comparatively little, the voltage rising rapidly to the gassing point. Cell *B* shows more local action, the rise in voltage being slower and the final voltage lower. In cell *C* the local action is pronounced, the final maximum voltage being reached only after about 4 hours' charging and being still lower than that of the other 2. The first sharp rise of voltage in curve *C* evidently corresponds to the charging of the positive plate, while the second rise is due to the negative plate.

Efficiency

The efficiency of a storage battery, that is the ratio of the output to the input, may be divided into 2 parts, namely, voltage efficiency and ampere-hour efficiency, the product (provided the charging rate is constant) being the energy or watt-hour efficiency. The voltage efficiency depends upon the difference between the charge voltage and the discharge voltage, the principal factor in this difference being the rates of charge and discharge. Obviously, at higher rates the discharge voltage will be lower and the charge voltage higher.

The ampere-hour efficiency depends upon 2 factors, *viz.*, the loss due to local action and that due to gassing during charge. The local action loss varies with the elapsed time as well as with the temperature, etc., and is independent of the amount of work done by the battery. The loss due to gassing depends entirely upon the charging conditions. If the local action loss is negligible compared to the work done, as is the case where the cycle is short and includes a considerable amount of discharge, the ampere-hour efficiency may be brought very close to 100 per cent by careful control of the charging rate below the gassing point.

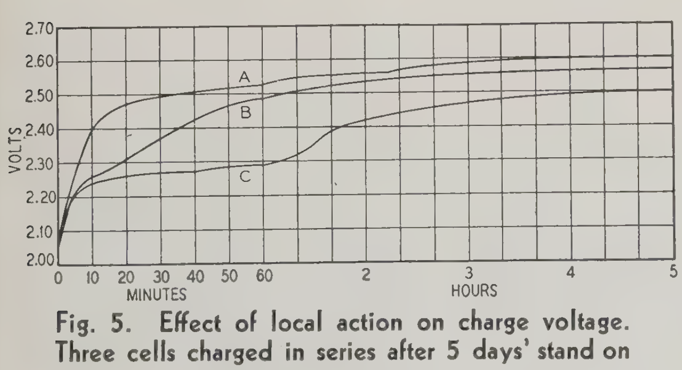
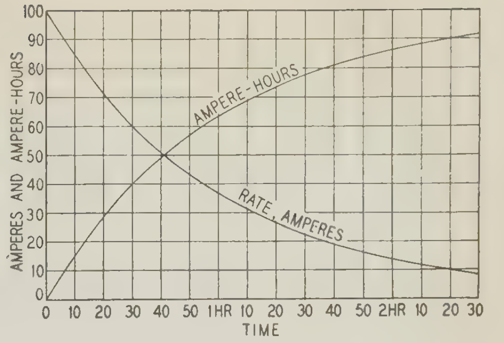


Fig. 5. Effect of local action on charge voltage. Three cells charged in series after 5 days' stand on open circuit

Fig. 6. Charging by ampere-hour law



Charging Rates—The Ampere-Hour Law

With these various phenomena in mind the groundwork has been laid for discussing the question of how to charge a discharged storage battery. This question may be divided into 2 principal parts: (1) what charging rates to use; and (2) how to determine when to stop the charge. As to charging rates, the general rule is that any rate may be used that does not cause violent gassing or excessive temperature. Just what rates may be used without exceeding these limits must be determined by experience. In the early stages of the charge comparatively high charging rates may be employed but as the charge progresses a point is reached when the rate should be reduced. As a result of numerous tests, it has been found that if the charging rate in amperes is kept below a value equal to the number of ampere-hours then out of the battery the conditions as to gassing and temperature will be met. For example, if the battery has been discharged to the extent of 100 ampere-hours, any rate less than 100 amperes may be used. When the charge has been continued until 10 ampere-hours have been put in, leaving 90 ampere-hours still out, the rate must be reduced below 90 amperes, etc., the rate being continually reduced or tapered to keep within the value fixed by the ampere-hour law. When the rate is finally reduced to the prescribed "finishing" rate for the particular type of battery, the charge may be finished at that rate without further reduction. This law may be expressed by the differential equation

$$di = -idt$$

which results from the condition that the charging rate i is continually reduced by the amount of charge in ampere-hours put in in the interval of time dt. The integration of this expression gives the exponential equation

$$i = A\epsilon^{-t}$$

in which i is the charging rate in amperes, t the time in hours, and A the ampere-hours out of the battery when the charge starts ($t = 0$). This law is shown graphically in figure 6 from which it will be noted that 90 per cent of the capacity taken out may be put back in 2 hours and 20 minutes.

While this ampere-hour law is entirely empirical it is useful as an approximate guide in determining

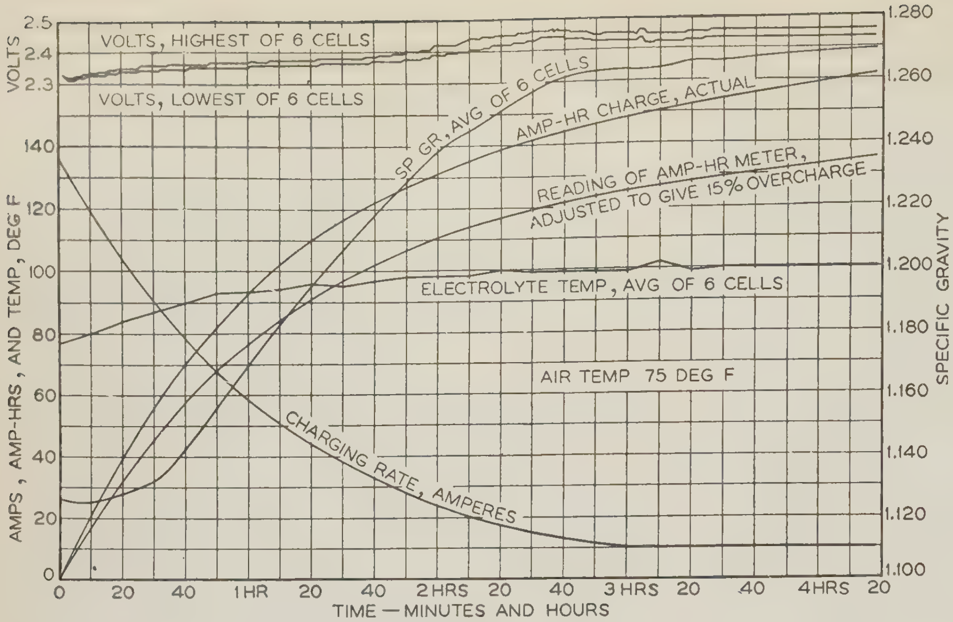


Fig. 7. Charge of 6 cells following a discharge equal to rated 6 hour capacity of 135 ampere-hours

Charging current in amperes kept equal to 135 minus ampere-hour meter reading

safe charging rates. Any lower rates may of course be used with a corresponding increase in the time required.

The accompanying diagram, figure 7, shows the results of another interesting test. A discharged battery was recharged in accordance with the ampere-hour law above mentioned, the charging rate being adjusted at frequent intervals to keep it equal to the ampere-hours out. The cell voltage was taken throughout the charge and it will be noted that this voltage is substantially constant until about 90 per cent of the previous discharge had been restored. This indicates that a fully discharged battery may be charged in about 4 hours by maintaining a constant voltage of about 2.4 volts per cell across the battery. At lower constant voltage, even as low as 2.15 volts per cell, the battery may be fully charged if sufficient time is available. Either of these 2 methods, that is, either a tapering charge, the rate being continually adjusted to follow the ampere-hour law, or the constant voltage method, will permit charging a battery in minimum time, the results being substantially the same in both. Each method presents certain disadvantages if minimum time is imperative. The first calls for constant manual control to maintain a carefully predetermined schedule of charging rates for given intervals of time. The second requires a practically constant voltage to be maintained, the correct value of which will depend upon the temperature of the cells. Both methods require a comparatively high capacity in the charging source to supply the initial charging rates.

The straight constant voltage method is also somewhat unstable if comparatively high voltage is employed since small variations of voltage or temperature cause excessive variations in the charging rates. Thus, an unobserved increase in voltage resulting in excessive charging rate will produce a rise in cell temperature causing a reduction in the counter electromotive force and a further increase of current, the effect being cumulative.

To obviate these disadvantages, the modified constant voltage method has been adopted and is very generally used for charging batteries in motive power and similar service. In this method, the voltage of the charging bus is maintained substantially constant at a value somewhat higher than that required for straight constant voltage charging, and a fixed resistance is included in the charging circuit. The time required for a complete charge is somewhat greater than with straight constant voltage but no manual control is required, the charging rate tapering down automatically as the charge progresses, and conditions are practically stable. The curves in figure 8 illustrate the results of constant voltage and modified constant voltage methods. Figure 9 shows the results of straight constant voltage charging at 2.15 volts and 2.27 volts per cell.

The methods above described permit establishing conditions for charging a battery safely in minimum time. If more time is available, lower charging rates may of course be used and in some respects are preferable, as they provide a greater margin of safety and call for less capacity in the charging source. The constant current method is entirely satisfactory, provided the rate is not greater than the prescribed finishing rate; or a 2 step charge may be used starting at a comparatively high rate and dropping to the finishing rate when appreciable gassing begins as indicated by the rapid rise of the charge voltage curve. As previously mentioned, very low charging rates throughout the entire charging period are entirely satisfactory, provided sufficient time is allowed to complete the charge, the principal difficulty in such cases being the less definite indication of the completion of the charge by maximum specific gravity and voltage.

Methods of Determining When to Stop Charge

The next question is how to determine when to stop the charge. How can one tell when a battery is fully charged? In the early days of storage battery development, the impression became rather firmly established that a final voltage of 2.5 per cell was the criterion. This idea was perpetuated in certain textbooks long after its fallacy had been demonstrated. It was usually tied in with a charging rate equal to the 8 hour discharge rate, but nothing was said about temperature or other factors

which affect the final voltage. Figure 10 shows a series of curves giving final charge voltage of a certain type of cell at different rates and temperatures. Different designs of cell will exhibit somewhat different characteristics. As a matter of fact, the actual voltage of a cell is a very unreliable indication of the completion of the charge. The specific gravity of the electrolyte is a better guide but even this requires certain precautions, since the specific gravity of a fully charged cell will vary with temperature and the height of the electrolyte, increasing at low temperatures and with reduction in level caused by loss of water from the electrolyte by evaporation and decomposition due to gassing. The most reliable indication is the attainment of maximum voltage and specific gravity, as indicated by a number of identical readings taken at stated intervals. Even then a temperature correction should be applied, if appreciable temperature change has occurred.

Ampere-Hour Meter for Stopping Charge

Another method for determining when a battery has been fully charged is to measure the ampere-hour output during the previous discharge, and continue the charge until the same number of ampere-hours have been put in plus a certain percentage of overcharge to compensate for losses. An ampere-hour meter is the most practical means for measuring the output and input, and these meters are designed to run slow in the charge direction by a certain percentage which may be adjusted within limits so that, when the indicator hand has returned to zero, the necessary overcharge will have been given. These meters are also provided with a contact at the zero point which may be used to trip a circuit breaker in the charging circuit and thus terminate the charge automatically.

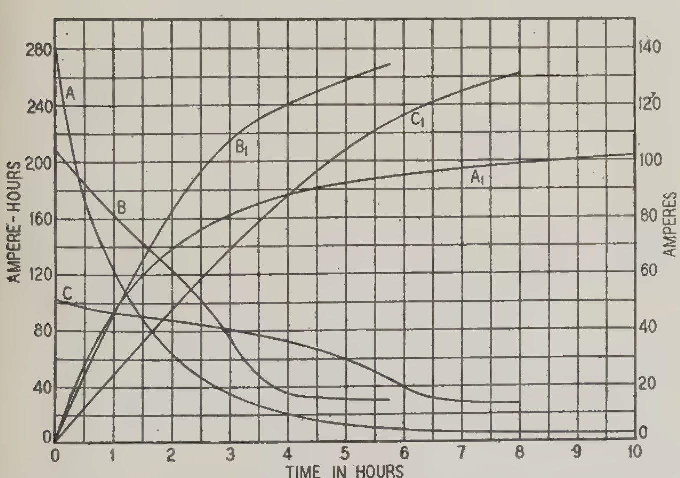


Fig. 8. Straight constant voltage and modified constant voltage charging

A, B, and C—Amperes
A_1, B_1, and C_1—Ampere-hours
A and A_1—Straight constant voltage charge at 2.25 volts per cell
B and B_1—Modified constant voltage charge. Bus voltage 2.53 volts per cell. Fixed resistance 0.00306 ohm per cell
C and C_1—Modified constant voltage charge. Bus voltage 2.63 volts per cell. Fixed resistance 0.0095 ohm per cell

The percentage of overcharge required will vary considerably under various operating conditions. In the case of daily discharges calling for nearly the full capacity of the battery followed by a recharge in 7 or 8 hours, a 15 per cent overcharge is usually satisfactory for lead-acid cells. It must be remembered, however, that practically all the loss due to gassing occurs at the end of the charge, and the overcharge in ampere-hours required to compensate for this is nearly constant for a given charging rate and independent of the amount of discharge. The *percentage* of overcharge required will therefore be greater if the operating cycle involves only a partial discharge. If the discharge is intermittent in character or at very low rates and therefore spread over a long period of time, calling for a recharge say once a week or less frequently, the loss due to local action may be appreciable in proportion to the total useful work, requiring a comparatively high percentage of overcharge.

The "Equalizing" Charge

On account of the difficulty of determining exactly how much overcharge is required by a battery subjected to daily cycles, and in order to avoid unnecessary overcharge, it is common practice to stop the daily charge a little short of full charge and give the battery a so-called "equalizing" charge at stated intervals, say once a week for service involving daily charges; this equalizing charge consists of a prolongation of the regular charge, at the finishing rate, until the proper values of specific gravity and voltage have been shown for a maximum period of one hour or longer, depending upon the rate of charge. The one hour maximum applies when the rate at end of charge is equal to the specified finishing rate for the cell. At lower rates, the maximum is longer in inverse ratio; for example, 3 hours at $^1/_3$ the finishing rate.

The purpose of the equalizing charge is to insure that occasionally every plate in every cell of the battery is brought with certainty to a state of full charge. This is especially important in respect to the negative plates. It is not to be expected that all the plates in a battery will remain exactly alike

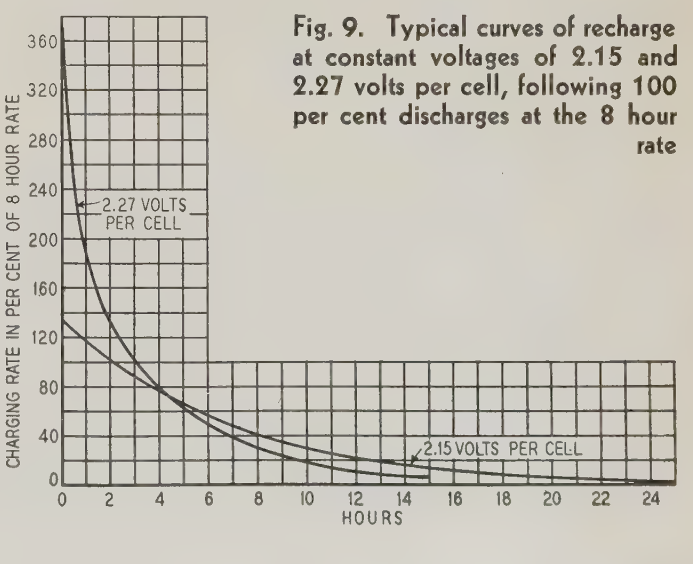


Fig. 9. Typical curves of recharge at constant voltages of 2.15 and 2.27 volts per cell, following 100 per cent discharges at the 8 hour rate

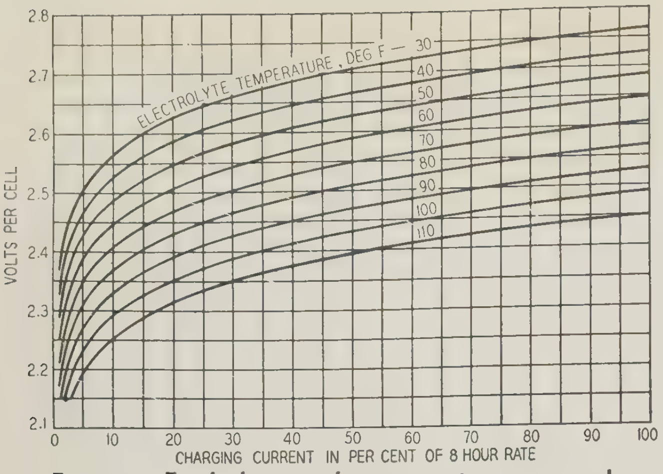


Fig. 10. Final charge voltage at various rates and temperatures

throughout its life, and those that develop a little more local action than the rest will probably not be fully charged at the end of the normal charge. The difference therefore is cumulative and can only be corrected by the equalizing charge.

Voltage Relay for Stopping Charge

For automatically terminating the charge another principle has been successfully employed. While a definite final voltage is not a reliable indication of the completion of the charge, the point where gassing begins and the voltage rises rapidly occurs at about the same state of charge for a given charging rate and temperature. Since the voltage curve is quite steep at this point a voltage value can be established say between 2.35 and 2.4 volts per cell which is certain to fall on this part of the curve, even with considerable variation in charging conditions, and a relay employed to respond to this voltage need not be designed for such extreme accuracy as to be impractical. This principle is used in several arrangements for the automatic control of battery charge. In one of these, the voltage relay starts a clock mechanism when the battery voltage reaches the selected value, and the clock, after running for a definite period of time, say 1 or 2 hours, opens a switch in the charging circuit and stops the charge. Other applications of this principle will be referred to later.

Constant Voltage Floating and Trickle Charging

Up to this point applications have been considered in which the battery is employed for "cycle" service—that is, it is discharged more or less completely in performing its work and is then taken out of service for recharging. Usually, as in motive power service, the work circuit and the charging circuit are independent of each other. In other cases, as in farm lighting, the charging source carries the load while the battery is being charged, the battery being used when the charging source is shut down.

In another and very extensive class of battery applications, the battery is constantly floating on the supply circuit, and kept fully charged except for occasional momentary discharges to carry the load peaks or for emergency discharges to tide over interruptions to the normal source of current. These applications may be conveniently divided into 2 classes, *viz.*, those in which the battery is continuously connected to a substantially *constant voltage* bus or circuit, and those in which the battery is continuously connected to the load circuit and a *constant current* is supplied to the circuit sufficient to carry the load and in addition to furnish a small trickle charge current to the battery to compensate for local action and keep the battery fully charged.

In the first, or "floating" system, the bus voltage is maintained at an average value equivalent to 2.15 volts per cell (assuming 1.215 specific gravity electrolyte) and it is desirable to keep this voltage as nearly constant as possible, since variations above and below the average value will cause the battery to charge and discharge, subjecting it to a certain amount of useless work. This constant voltage floating automatically compensates for the effects of varying temperatures, since at higher temperatures the battery will take more current at the same voltage, thus compensating for the corresponding increase in local action. In these strictly constant voltage floating systems the operating conditions for the battery are independent of the load since, if the voltage of the source is not affected by load fluctuations, such fluctuations must fall on the source and not on the battery. In certain installations falling essentially in this class, the generator is designed with a flat-compound characteristic up to full load, at which point the voltage drops off decidedly with further increase of load. Such a combination is ideal for handling a combination of load in which a part of the load is steady but may vary from time to time while upon this steady load is superimposed intermittent momentary demands of considerable magnitude. Under these conditions the generator will handle the trickle charge for the battery and the variations in the steady load, assuming that these do not exceed the range over which the generator voltage is constant, while the momentary demands beyond this range are carried largely by the battery. These momentary discharges amount to very little in ampere-hours compared to the battery capacity so that the actual work falling on the battery is relatively light. It should be noted that the term "flat-compounded" in this case must be literally interpreted as signifying a voltage characteristic that is substantially constant over the entire range from no load to full load, and not merely equal at full load and no load with a hump between.

Intermittent Charge With Constant Discharge

There is another class of battery applications in which the load circuit carrying a variable load is constantly connected to the battery, while the charging source is available only at more or less frequent intervals. A typical example is the usual railway axle-lighting system. Here constant voltage control of the charging generator is employed (modified to

prevent overloading the machine), but on account of the intermittent application of the charging source a higher value of constant voltage must be used than the 2.15 volts per cell adopted for continuous floating. Owing to the uncertainty as to the proportionate time during which the charging source is available as well as the variation in amount of discharge, under different operating schedules, it is impossible to determine an ideal value for the constant voltage to be maintained when the generator is running, and in order to minimize the possibility of a discharged battery and a resulting light failure, the generator voltage is controlled at a point which produces some overcharging under average operating conditions, a voltage of 37 to 38 volts for 16 cells being usual. This will recharge a discharged battery rapidly but will not produce injurious overcharging, considering the small proportion of the time each day during which the battery is subjected to this voltage while fully charged. The effect of this constant voltage control of an axle lighting generator in compensating for variations in operating conditions is shown in figure 11, which is taken from the chart of a graphic ammeter recording the ampere output of the generator. The area above the lamp load line represents the charge to the battery. It will be noted that after each stop, during which the battery is discharging to carry the lamp load, the generator output is maintained at a comparatively high value until the amount of the previous discharge has been restored, whereupon the generator output automatically drops to a low value continuing the battery charge at a comparatively low rate. The difference between the charge following a 10 minute stop and that following a 1 minute stop is quite marked.

Various Cases Involving Automatic Control

The next cases to be considered are those in which the source of current has a decidedly drooping voltage characteristic, adapted to furnish a substantially constant current, and is continuously connected across the battery. These cases present a number of interesting problems in automatic control, depending on the character of the load. A few typical examples will be considered.

Take, first, the case where the only load is an occasional momentary demand, occurring at infrequent intervals, as in many railway signal systems. Here it is sufficient to supply from the source a constant current equal to the trickle charge current required by the battery plus a small surplus equal to the average value of the intermittent load. It is then neces-

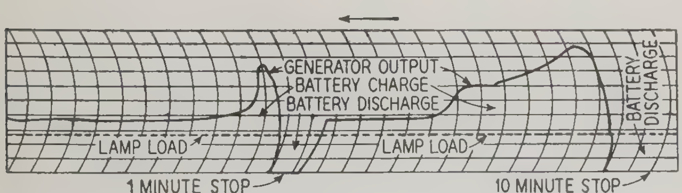


Fig. 11. Chart of graphic ammeter recording output of axle-lighting generator, controlled for constant voltage

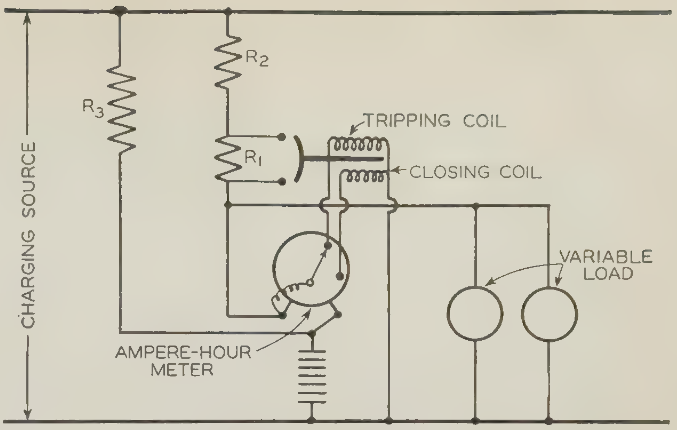


Fig. 12. Two step charge control with ampere-hour meter

sary to adjust to the proper value the output from the source (which is generally a rectifier connected to the a-c transmission line). The most satisfactory way to do this is to note the floating voltage of the battery and make the adjustment such as to maintain this at an average of 2.15 volts per cell. This adjustment should not be attempted until some time has elapsed after the termination of a discharge to permit stable conditions to be re-established. In making such adjustment it must be borne in mind that the battery voltage responds rather slowly to a small change in the charging current so that time must be allowed, after making a tentative adjustment, before deciding that such adjustment is correct. Furthermore, since the ouput of these rectifiers is a substantially constant current, varying but little with temperature or battery voltage, and since the battery requires more trickle charge current in warm weather than in cold weather, ideal conditions would call for readjustment in the spring and fall. Where this is not practical it is better to adjust for summer temperatures and allow the battery to be somewhat overcharged in winter. After a prolonged discharge due to a power outage, the output of the rectifier should be temporarily increased until the discharge has been restored. If, in addition to the intermittent load there is also a constant steady load, the output of the rectifier is increased by the amount necessary to provide for this, so that the battery is still called upon to take only the intermittent momentary demands.

Consider now the case where there is a more or less variable steady load with or without intermittent momentary demands as in some telephone installations. If the average value of these combined loads can be predetermined or at least closely approximated, the output of the rectifier or other source of constant current may be adjusted to this average value plus the necessary trickle charge for the battery. The latter will be maintained in a state of charge approaching full charge, but it will of course discharge when the load is greater than the output from the source and will charge when the load is less.

If, however, the load varies in a manner that cannot be predetermined and the fluctuations are appreciable as compared with the ampere-hour capacity of the battery it is important to provide automatic

means for adjusting the output from the source from time to time to correspond with these load fluctuations and prevent the battery from being subjected either to over-discharge or overcharge. Various types and combinations of apparatus have been developed for effecting this automatic control which will now be discussed.

Two Step Control With Ampere-Hour Meter

One of these schemes is shown in the accompanying diagram, figure 12. A 2 step resistance is connected between the charging source and the circuit to which the battery and the load are connected, with a contactor arranged to short-circuit a part of the resistance. An ampere-hour meter is permanently connected into the battery circuit with 2 auxiliary contacts, one at the full charge point and the other at a point corresponding to a certain percentage discharge. The first contact is connected to the tripping coil of the contactor and the second to the closing coil. Thus when the arm of the ampere-hour meter is at zero, indicating that the battery is fully charged, the contactor is tripped open and the minimum current is transmitted from the source. This should be adjusted to give the battery its normal trickle charge rate when the load is at its minimum value. Whenever the load is appreciably greater than this minimum, the battery will discharge until the arm of the ampere-hour meter reaches the second contact, when the contactor will be closed, and the maximum current will be transmitted from the source. This maximum current should be sufficient to insure that the battery will be recharged. This maximum current may be greater or less than the maximum load depending upon the duration of the latter. Thus, if the maximum load is of short duration the maximum current from the source may be considerably less and still recharge the battery when the load is less than its maximum. The ampere-hour meter is adjusted to run slow in the charge direction to provide the necessary overcharge; however, as already pointed out, this adjustment is usually only approximately correct but this inaccuracy may be compensated for by the proper adjustment of the low or trickle charge rate.

As a further refinement, a comparatively high resistance, shown on the diagram at R_3, may be connected to transmit from the source directly to the battery, without passing through the ampere-hour meter, a trickle charge current sufficient to compensate for local action. This arrangement is theoretically correct since the local action current does not register on the ampere-hour meter. The total charging resistance, i. e., the sum of R_1 and R_2, would then be adjusted to provide for the minimum load without any excess.

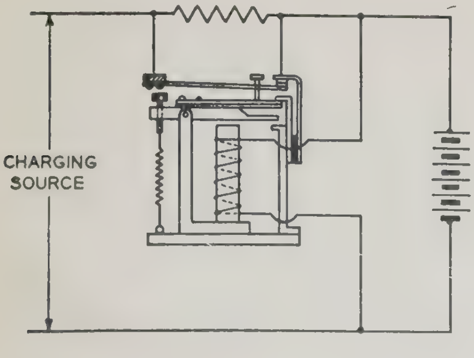


Fig. 13. Temperature compensated relay for 2 step charge control

This ampere-hour meter control of a 2 rate charge has been used successfully in a number of battery installations, but it has certain inherent defects. It necessarily throws on the battery a certain amount of work, at least a part of which could be carried by the source, and as already pointed out, the overcharge adjustment of the ampere-hour meter is only approximate. If set too low, the battery will be starved and a battery failure may result. To guard against this, the tendency will always be to set the overcharge too high. Another difficulty lies in the fact that at very low currents the ampere-hour meter is inaccurate and may fail to register.

Two Step Control With Voltage Relay

Another method of controlling a 2 rate charging scheme is by means of the voltage relay already referred to. The exciting coil of this relay is connected directly across the battery terminals, and when the battery voltage reaches a value corresponding to a point on the charge voltage curve where gassing begins and the voltage rises rapidly, the relay operates to reduce the charging rate from the high to the low value. The battery is not fully charged at this point, but the low rate may be so adjusted that the charge will in time be completed, yet the charge may be continued at this rate without injurious overcharge. It is then necessary to provide for re-establishing the higher rate of charge as may be required, which is accomplished by momentarily opening the circuit of the voltage relay exciting coil. This may be effected by a second relay whose exciting coil is connected into the load circuit, so that whenever the load is thrown on, the higher rate is restored. If the load is thrown on and off manually, as is often the case in telephone service, an auxiliary contact on the load switch may be used.

Another method is to re-establish the higher rate at definite time intervals, regardless of the load. For this purpose a slowly revolving contact-making disk may be employed, driven by a small a-c motor such as is used in electric clocks.

This 2 rate charging scheme controlled by a voltage relay is proving very satisfactory. It automatically adjusts the amount of charge to varying load conditions. If the battery has been subjected to an appreciable amount of discharge, the high-rate charge will be maintained for a longer time before the voltage relay acts than if the discharge has been less.

In a further modification of this method only a single charging rate is provided, sufficient to take care of the maximum requirements, and when the battery voltage reaches the value for which the voltage relay is adjusted, the charge is entirely cut off until it is re-established after a definite time interval by means of the timing device. It is found that even without the trickle charge rate following the high charge rate, the battery can be fully recharged if

the high charge rate is applied at sufficiently frequent intervals even though the voltage relay cuts off the charge at a voltage which would not ordinarily correspond to the fully charged state.

If the battery is subjected to considerable variation of temperature, the voltage relay should be provided with automatic temperature adjustment since the voltage corresponding to a given state of charge with the same charging rate will be higher at lower temperatures. A voltage relay designed for this purpose, with temperature compensation, is shown in figure 13. The temperature compensation is effected by means of a bimetallic strip attached at one end to the armature while the other end bears against a fixed stop. Increase of temperature causes the bimetallic strip to move the armature nearer to the magnet poles, thus reducing the air gap and causing the relay to function at a lower voltage.

In following up these automatic charging schemes, it is necessary to ascertain whether the adjustments of the various factors, such as time intervals, charging rates, and cut off voltage are correct to maintain the battery properly, giving it sufficient charge to make up for the discharges and the losses without an unnecessary amount of overcharge. The accuracy of these adjustments can be determined by 2 observations, first the specific gravity of the electrolyte and second the amount of water required for refilling. If the charge is not sufficient, the specific gravity of the electrolyte will gradually fall off. If the charge is excessive, this will be indicated by an excessive amount of water required for maintaining the level of the electrolyte in the cells. The normal amount of water required for different types of cell over a given period of time can be obtained from the manufacturer as a guide in following up these automatic installations.

The "Float-Meter"

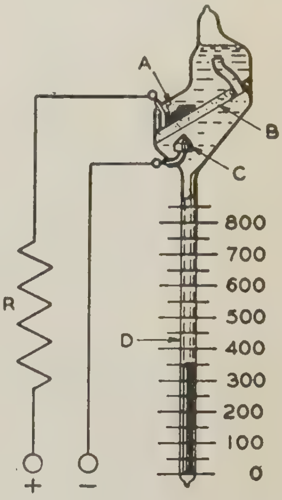
Another device has recently been developed called a "float-meter," designed to indicate the *average* voltage which has been maintained across the battery terminals over a given period of time. In many situations, this floating voltage is subject to appreciable variation at different times of the day or from day to day, and it is quite burdensome or wholly impractical to take voltage readings at sufficiently frequent intervals to determine the true average. This float-meter is of the electrolytic type in which mercury is deposited from a solution of a mercury salt on the cathode from which it drips into a tube of small diameter provided with an appropriate scale indicating the amount of mercury thus deposited in a given length of time. This instrument gives accurate measurements where the current is but a few milliamperes, and by connecting it in series with a high resistance across the battery terminals it indicates *average impressed voltage*. The scale is so chosen that the quotient obtained by dividing the reading by the time interval in hours will equal the average voltage during that interval. (See figure 14.)

This meter must be reset periodically, when the measuring tube becomes filled with mercury, by tilting the tube so as to transfer the mercury to the anode reservoir. These limitations are not, however, seriously objectionable in this particular application.

Control for Automobile Batteries

The design of automatic equipment for charging the starting and lighting battery on an automobile presents some additional problems owing to limitations imposed by considerations of space, cost, and

Fig. 14. Schematic diagram of "float-meter" for registering average voltage over a given time period



wiring. This problem was not so serious when lighting loads were comparatively small, the battery capacity being determined by the starting requirements. The generator output required to supply the lights and ignition did not constitute a very excessive charging rate for the battery when the lights were turned off, especially in view of the usual characteristic of the third brush generator whereby the output is appreciably reduced at the high speeds usual in prolonged summer touring by daylight. The recent increase in the steady load requirements for radio, more powerful lights, heaters, defrosters, and other accessories has led to marked increase in generator output with little or no increase in battery size to meet starting requirements, and unless provision is made for automatically reducing the output when the battery is full and the load is cut off serious overcharging results. Two kinds of automatic control equipments have recently been developed to take care of this problem. In one, constant voltage regulation is provided for the generator (instead of the constant current characteristic of the third brush machine) modified to prevent generator overload when the battery is in a discharged condition and the load is connected; while the other provides constant current output of 2 different values, controlled by battery voltage and in some cases also by the closing of the load switch. Adjustment of the voltage responsive control devices for winter and summer temperatures is important and is provided in some of these recently developed equipments.

The curves and data given herein are typical or illustrative and subject to variation with differences of cell design such as density and volume of electrolyte, plate thickness and spacing, and composition and distribution of the active material.

An Analysis of the Induction Motor

For problems involving induction motors other than the usual balanced winding type operating under steady-state conditions, a general method of analysis is necessary. In this paper, a general analysis is presented, and in particular, its use in short-circuit problems is described. The comparison between tests and calculated results indicates that the method does properly describe induction motor phenomena.

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THOUGH much has been written about the analysis of induction motors when operating at constant speed and driving a steady load, comparatively little has been published concerning the analysis of induction motors when driving pulsating loads, or when short circuits are applied, or when special cases of winding unbalance occur. (Two papers known to the writer to have dealt with these problems are listed at the end of this paper.) It is the aim of the present paper to present an analysis which makes it possible to deal with any induction motor under any condition of operation, and to present the results obtained in solving several problems involving short circuits on induction motors.

Preliminary Discussion

From the foregoing, it may be correctly inferred that practically any induction motor may be analyzed by the method to be described, but of course, subject to the assumptions which are made in the analysis. Since, obviously, in a paper of this nature it is impossible to deal specifically with all possible induction motors, the method is applied to the balanced 3 phase induction motor. From this, the method by which any other induction motor may be treated will be evident.

For the purpose of determining short-circuit currents, it is sufficient to deal only with relationships of instantaneous voltages, currents, and speed. Thus, this paper may be said to deal with the general $e = iz$ relations of the induction motor; e, i, and z representing, of course, voltage, current, and impedance, respectively.

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General $e = iz$ Relations

Assumptions. The following major assumptions are to be made in the derivation of these general relations.

1. Magnetic saturation is negligible.
2. Core losses are negligible.
3. Changes in resistance due to heating are small.

Derivation. The derivation of the general relations depends entirely upon the following general relation for any electric circuit:

$$e = ri + p\psi 10^{-8} \tag{1}$$

where

e = instantaneous voltage *applied* to the circuit, volts
i = instantaneous current into the circuit from the positive terminal of applied voltage, amperes
r = circuit resistance, ohms
ψ = instantaneous flux linkages with circuit including linkages due to current in coupled circuit such mutual linkages being taken as positive when they are in the same direction as self-linkages due to positive circuit current
p = derivative operator indicating that derivative with time is to be taken.

From the definition of self and mutual inductance, it is evident that equation 1 may be written as

$$e = ri + p(Li) + \sum_n p(M_n i_n) \tag{2}$$

where

Li = self-linkages $\times 10^{-8}$
$M_n i_n$ = mutual linkages $\times 10^{-8}$

and the summation sign is used to indicate that there may be several mutually coupled circuits.

Now, in a 3 phase induction motor, there are 6 electric circuits, 3 on the stator and 3 on the rotor. Each winding has a self-inductance. Mutual inductance exists between stator phases, between rotor phases, and between stator and rotor phases. The self-inductances are substantially constant, the slight variations due to the motion of a slotted rotor by a slotted stator being negligible in effect for a well designed motor. Similarly, the mutual inductance between 2 stator phases or 2 rotor phases is essentially constant.

However, the mutual inductance between a stator phase and a rotor phase is not constant but depends upon the position of the rotor phase with respect to the stator phase. When the magnetic axes of a stator phase and a rotor phase are opposite each other, the mutual inductance is a maximum; when they are displaced $\frac{\pi}{2}$ electrical radians the mutual inductance has a zero value. To a very close approximation, this "across the gap" mutual inductance varies as the cosine of the electrical angle between the magnetic axes of the windings.

In figure 1*a* is shown a circuit diagram of the 3 phase induction motor. In figure 1*b* is shown a diagram of an instantaneous relation between the positions of the magnetic axes of the 6 circuits or windings.

In figure 1*b*, the angle θ is the instantaneous electrical angle in radians between a reference stator

phase and a reference rotor phase, in this case taken to be the a stator phase and the a rotor phase.

From the figures drawn and from the discussion on flux linkage above it follows at once that,

$$\left.\begin{aligned}
10^{-8}\psi_{a1} &= L_1 i_{a1} + M_1 i_{b1} + M_1 i_{c1} + M\cos\theta i_{a2} + \\
&\qquad M\cos\left(\theta + \frac{2\pi}{3}\right) i_{b2} + M\cos\left(\theta + \frac{4\pi}{3}\right) i_{c2} \\
10^{-8}\psi_{b1} &= M_1 i_{a1} + L_1 i_{b1} + M_1 i_{c1} + \\
&\quad M\cos\left(\theta + \frac{4\pi}{3}\right) i_{a2} + M\cos\theta i_{b2} + M\cos\left(\theta + \frac{2\pi}{3}\right) i_{c2} \\
10^{-8}\psi_{c1} &= M_1 i_{a1} + M_1 i_{b1} + L_1 i_{c1} + M\cos\left(\theta + \frac{2\pi}{3}\right) i_{a2} + \\
&\qquad M\cos\left(\theta + \frac{4\pi}{3}\right) i_{b2} + M\cos\theta\, i_{c2}
\end{aligned}\right\} \quad (3)$$

$$\left.\begin{aligned}
10^{-8}\psi_{a2} &= L_2 i_{a2} + M_2 i_{b2} + M_2 i_{c2} + M\cos\theta\, i_{a1} + \\
&\qquad M\cos\left(\theta - \frac{2\pi}{3}\right) i_{b1} + M\cos\left(\theta - \frac{4\pi}{3}\right) i_{c1} \\
10^{-8}\psi_{b2} &= M_2 i_{a2} + L_2 i_{b2} + M_2 i_{c2} + M\cos\left(\theta - \frac{4\pi}{3}\right) i_{a1} + \\
&\qquad M\cos\theta\, i_{b1} + M\cos\left(\theta - \frac{2\pi}{3}\right) i_{c1} \\
10^{-8}\psi_{c2} &= M_2 i_{a2} + M_2 i_{b2} + L_2 i_{c2} + M\cos\left(\theta - \frac{2\pi}{3}\right) i_{a1} + \\
&\qquad M\cos\left(\theta - \frac{4\pi}{3}\right) i_{b1} + M\cos\theta\, i_{c1}
\end{aligned}\right\} \quad (4)$$

where

L_1 = self-inductance of a stator phase in henrys
L_2 = self-inductance of a rotor phase in henrys
M_1 = mutual inductance between stator phases in henrys
M_2 = mutual inductance between rotor phases in henrys
M = maximum mutual inductance between any stator phase and any rotor phase

Also from figure 1a, the following relations between currents are seen to exist.

$$\left.\begin{aligned}
i_{a1} + i_{b1} + i_{c1} &= 0 \\
i_{a2} + i_{b2} + i_{c2} &= 0
\end{aligned}\right\} \quad (5)$$

To simplify expressions 3 and 4 the relations 5 are introduced and the trigonometric functions are expanded. The result is written as follows:

$$\left.\begin{aligned}
10^{-8}\psi_{a1} &= (L - M_1) i_{a1} + \\
&\qquad \frac{3}{2} M\left[\cos\theta\, i_{a2} - \frac{1}{\sqrt{3}}\sin\theta\,(i_{b2} - i_{c2})\right] \\
10^{-8}\psi_{b1} &= (L_1 - M_1) i_{b1} + \\
&\qquad \frac{3}{2} M\left[\cos\theta\, i_{b2} - \frac{1}{\sqrt{3}}\sin\theta\,(i_{c2} - i_{a2})\right] \\
10^{-8}\psi_{c1} &= (L_1 - M_1) i_{c1} + \\
&\qquad \frac{3}{2} M\left[\cos\theta\, i_{c2} - \frac{1}{\sqrt{3}}\sin\theta\,(i_{a2} - i_{b2})\right]
\end{aligned}\right\} \quad (6)$$

$$\left.\begin{aligned}
10^{-8}\psi_{a2} &= (L_2 - M_2) i_{a2} + \\
&\qquad \frac{3}{2} M\left[\cos\theta\, i_{a1} + \frac{1}{\sqrt{3}}\sin\theta\,(i_{b1} - i_{c1})\right] \\
10^{-8}\psi_{b2} &= (L_2 - M_2) i_{b2} + \\
&\qquad \frac{3}{2} M\left[\cos\theta\, i_{b1} + \frac{1}{\sqrt{3}}\sin\theta\,(i_{c1} - i_{a1})\right] \\
10^{-8}\psi_{c2} &= (L_2 - M_2) i_{c2} + \\
&\qquad \frac{3}{2} M\left[\cos\theta\, i_{c1} + \frac{1}{\sqrt{3}}\sin\theta\,(i_{a1} - i_{b1})\right]
\end{aligned}\right\} \quad (7)$$

Now, the quantity $L_1 - M_1$ is none other than the apparent self-inductance of the 3 phase induction motor stator winding. It is the stator self-inductance used in the familiar equivalent circuit. Similarly, $L_2 - M_2$ is the apparent 3 phase self-inductance of a rotor winding and $\frac{3}{2}M$ is the apparent mutual or magnetizing inductance. To work in terms of these more familiar constants, the true machine inductances are redefined.

$$\left.\begin{aligned}
L_1 - M_1 &= L_1' \\
L_2 - M_2 &= L_2' \\
\frac{3}{2} M &= M'
\end{aligned}\right\} \quad (8)$$

As will be brought out very soon, the quantities $\psi_{a1} - \psi_{b1}$, $\psi_{b1} - \psi_{c1}$, $\psi_{a2} - \psi_{b2}$, and $\psi_{b2} - \psi_{c2}$, are of interest. Using the new symbols for inductance, and equations 6 and 7,

$$\left.\begin{aligned}
10^{-8}(\psi_{a1} - \psi_{b1}) &= L_1'(i_{a1} - i_{b1}) + \\
&\qquad M'\left[\cos\theta\,(i_{a2} - i_{b2}) + \sqrt{3}\sin\theta\, i_{c2}\right] \\
10^{-8}(\psi_{b1} - \psi_{c1}) &= L_1'(i_{b1} - i_{c1}) + \\
&\qquad M'\left[\cos\theta\,(i_{b2} - i_{c2}) + \sqrt{3}\sin\theta\, i_{a2}\right]
\end{aligned}\right\} \quad (9)$$

$$\left.\begin{aligned}
10^{-8}(\psi_{a2} - \psi_{b2}) &= L_2'(i_{a2} - i_{b2}) + \\
&\qquad M'\left[\cos\theta\,(i_{a1} - i_{b1}) - \sqrt{3}\sin\theta\, i_{c1}\right] \\
10^{-8}(\psi_{b2} - \psi_{c2}) &= L_2'(i_{b2} - i_{c2}) + \\
&\qquad M'\left[\cos\theta\,(i_{b1} - i_{c1}) - \sqrt{3}\sin\theta\, i_{a1}\right]
\end{aligned}\right\} \quad (10)$$

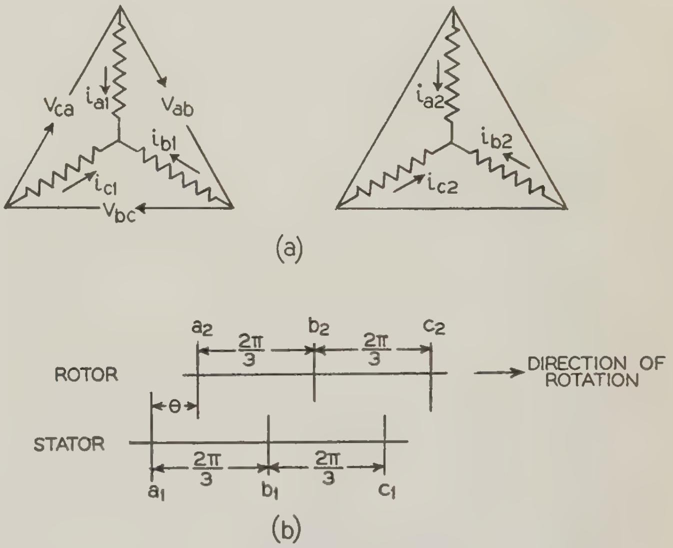

Fig. 1. Circuit diagram of the 3 phase induction motor (above) and an instantaneous relation between the positions of the magnetic axes of the 6 circuits or windings (below)

Using the fundamental relation given in equation 1, the following may be written for each of the motor phases:

$$\left.\begin{aligned}
e_{a1} &= r_1 i_{a1} + p\psi_{a1}\, 10^{-8} \\
e_{b1} &= r_1 i_{b1} + p\psi_{b1}\, 10^{-8} \\
e_{c1} &= r_1 i_{c1} + p\psi_{c1}\, 10^{-8}
\end{aligned}\right\} \quad (11)$$

$$\left.\begin{aligned}
e_{a2} &= r_2 i_{a2} + p\psi_{a2}\, 10^{-8} \\
e_{b2} &= r_2 i_{b2} + p\psi_{b2}\, 10^{-8} \\
e_{c2} &= r_2 i_{c2} + p\psi_{c2}\, 10^{-8}
\end{aligned}\right\} \quad (12)$$

where

r_1 = stator resistance per phase in ohms
r_2 = rotor resistance per phase in ohms

Since the applied voltages are known, the foregoing equations are written in terms of the applied voltages by direct reference to figure 1a:

$$\left.\begin{aligned}
V_{ab} &= e_{a1} - e_{b1} = r_1(i_{a1} - i_{b1}) + p10^{-8}(\psi_{a1} - \psi_{b1}) \\
V_{bc} &= e_{b1} - e_{c1} = r_1(i_{b1} - i_{c1}) + p10^{-8}(\psi_{b1} - \psi_{c1})
\end{aligned}\right\} \quad (13)$$

$$\left.\begin{aligned}
o &= e_{a2} - e_{b2} = r_2(i_{a2} - i_{b2}) + p10^{-8}(\psi_{a2} - \psi_{b2}) \\
o &= e_{b2} - e_{c2} = r_2(i_{b2} - i_{c2}) + p10^{-8}(\psi_{b2} - \psi_{c2})
\end{aligned}\right\} \quad (14)$$

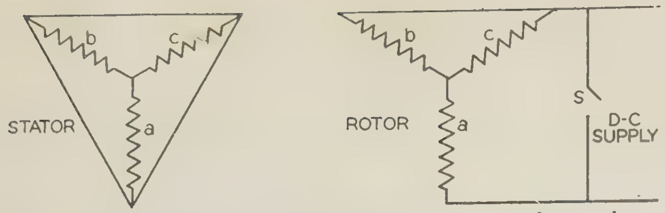

Fig. 2. Connections of induction motors subjected to tests for short-circuit currents

Now using the results of expressions 9 and 10

$$\left.\begin{aligned} V_{ab} &= (r_1 + pL_1')(i_{a1} - i_{b1}) + pM' \left[\cos\theta\,(i_{a2} - i_{b2}) + \sqrt{3}\sin\theta\, i_{c2}\right] \\ V_{bc} &= (r_1 + pL_1')(i_{b1} - i_{c1}) + pM' \left[\cos\theta\,(i_{b2} - i_{c2}) + \sqrt{3}\sin\theta\, i_{a2}\right] \end{aligned}\right\} \quad (15)$$

$$\left.\begin{aligned} 0 &= (r_2 + pL_2')(i_{a2} - i_{b2}) + pM' \left[\cos\theta\,(i_{a1} - i_{b1}) - \sqrt{3}\sin\theta\, i_{c1}\right] \\ 0 &= (r_2 + pL_2')(i_{b2} - i_{c2}) + pM' \left[\cos\theta\,(i_{b1} - i_{c1}) - \sqrt{3}\sin\theta\, i_{a1}\right] \end{aligned}\right\} \quad (16)$$

These equations in conjunction with the current equations 5 may be used to solve for any of the phase currents. As is shown in appendix I the stator currents can be expressed by the 3 relations

$$V_{ab} = \left\{Z_1(p) - pM'\left[\cos\theta \frac{pM'}{Z_2(p)}\cos\theta + \sin\theta \frac{pM'}{Z_2(p)}\sin\theta\right]\right\}(i_{a1} - i_{b1}) + \sqrt{3}\, pM'\left\{\cos\theta \frac{pM'}{Z_2(p)}\sin\theta - \sin\theta \frac{pM'}{Z_2(p)}\cos\theta\right\} i_{c1} \quad (22)$$

$$V_{bc} = \left\{Z_1(p) - pM'\left[\cos\theta \frac{pM'}{Z_2(p)}\cos\theta + \sin\theta \frac{pM'}{Z_2(p)}\sin\theta\right]\right\}(i_{b1} - i_{c1}) + \sqrt{3}\, pM'\left\{\cos\theta \frac{pM'}{Z_2(p)}\sin\theta - \sin\theta \frac{pM'}{Z_2(p)}\cos\theta\right\} i_{a1} \quad (23)$$

$$i_{a1} + i_{b1} + i_{c1} = 0 \quad (24)$$

where

$$\left.\begin{aligned} Z_1(p) &= r_1 + pL_1' \\ Z_2(p) &= r_2 + pL_2' \end{aligned}\right\} \quad (25)$$

These 3 simultaneous differential equations may be solved (at least theoretically) for the 3 stator currents. In these equations instantaneous values of motor currents, motor voltage, and motor speed are related, subject to the restrictions already stated. They then are the general $e = iz$ relations.

Short-Circuit Currents

To illustrate the use of these general relations, problems involving short circuits of induction motors turning at constant speed are considered. The transient currents attendant upon induction motor short circuits decay to a very small value in a short time. It is reasonable to consider that the rotor turns at constant speed during this time, the speed which it had at the instant before short-circuit. Thus, the first step in determining the short-circuit currents is to reduce the general relations to the constant speed relations.

From the definition of the angle θ it follows that,

$$\theta = \alpha + \int_0^t u\,dt = \alpha + ut \quad (26)$$

where

t is measured from the instant of short circuit
α = initial angle between phase a of stator and phase a of rotor
u = constant rotor speed in electrical radians per second

If this value of θ is introduced into equations 22, there results,

$$V_{ab} = \left\{Z_1(p) - M'^2\left[\frac{p(p+ju)}{Z_2(p+ju)} + \frac{p(p-ju)}{Z_2(p-ju)}\right]\right\}(i_{a1} - i_{b1}) + \frac{\sqrt{3}}{2j} M'^2\left[\frac{p(p+ju)}{Z_2(p+ju)} - \frac{p(p-ju)}{Z_2(p-ju)}\right] i_{c1} \quad (27)$$

The equation corresponding to equation 23 is obvious. Lack of space does not permit including the detailed procedure involved in obtaining equation 27 from equations 22 and 26.

At this point 2 fundamental motor impedances are defined; they should be noted carefully.

$$Z_{F1}(p) = Z_1(p) - M'^2 \frac{p(p-ju)}{Z_2(p-ju)} \quad (28)$$

$$Z_{B1}(p) = Z_1(p) - M'^2 \frac{p(p+ju)}{Z_2(p+ju)} \quad (29)$$

If a descriptive equivalent is required for these definitions they may be described as,

$Z_{F1}(p)$ = generalized constant speed positive phase sequence impedance of an induction motor viewed from the stator
$Z_{B1}(p)$ = generalized constant speed negative phase sequence impedance of an induction motor viewed from the stator

Substituting equations 28 and 29 into equation 27 there results

$$V_{ab} = \frac{Z_{F1}(p) + Z_{B1}(p)}{2}(i_{a1} - i_{b1}) - j\sqrt{3}\,\frac{Z_{F1}(p) - Z_{B1}(p)}{2}\, i_{c1} \quad (30)$$

Corresponding to equation 23 there is,

$$V_{bc} = \frac{Z_{F1}(p) + Z_{B1}(p)}{2}(i_{b1} - i_{c1}) - j\sqrt{3}\,\frac{Z_{F1}(p) - Z_{B1}(p)}{2}\, i_{a1} \quad (31)$$

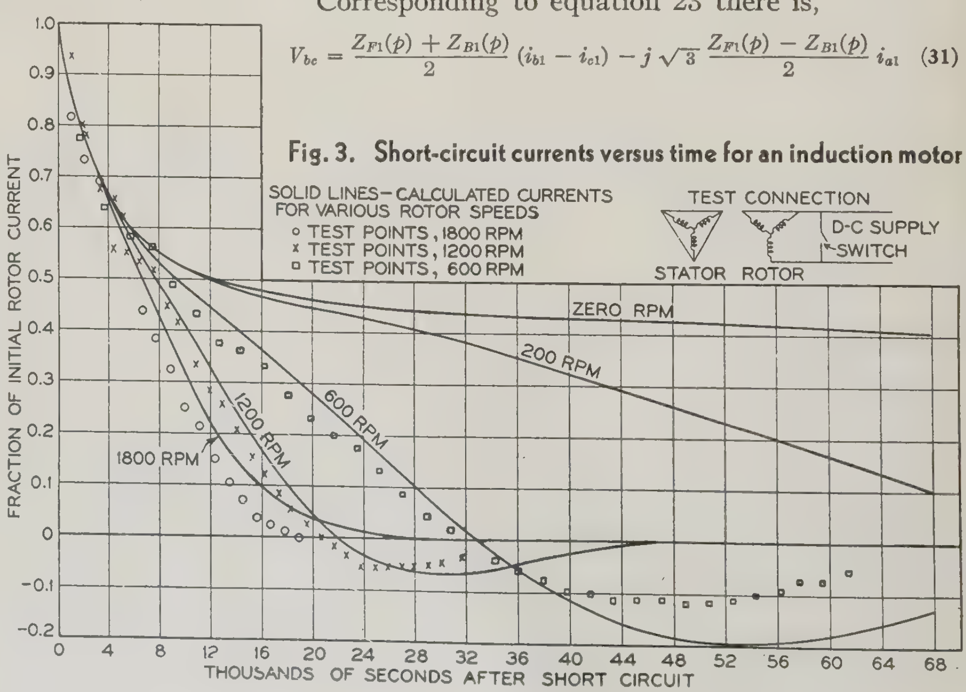

Fig. 3. Short-circuit currents versus time for an induction motor

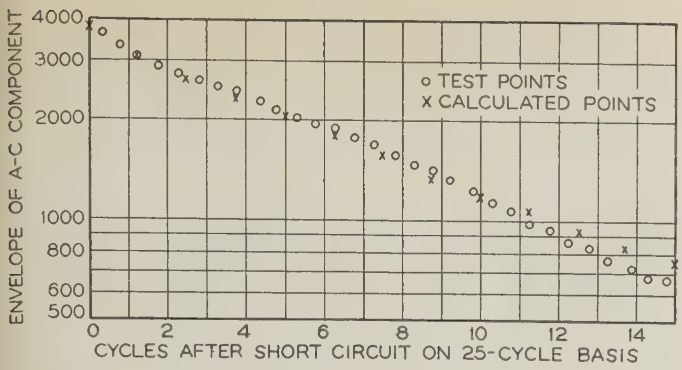

Fig. 4. Short-circuit current versus time for a Scherbius frequency converter

12,500 kva set, self-excited
External short circuit impedance equals 20 per cent reactance and 9.75 per cent resistance

The third equation completing the simultaneous set is of course equation 24.

The voltages applied to the motor stator are, for such cases as a simultaneous 3 phase short circuit,

$$V_{ab} = V_s \epsilon^{j\omega t} \epsilon^{j\beta} (1 - \mathbf{1}) \tag{32}$$
$$V_{bc} = V_s \epsilon^{j\omega t} \epsilon^{j\beta} \epsilon^{-j2\pi/3} (1 - \mathbf{1}) \tag{33}$$

where

V_s = peak value of line voltage, volts
ω = frequency of line voltage, electrical radians per second
β = initial electrical angle of voltage wave measured in electrical radians from positive peak of voltage
$\mathbf{1}$ = unit function, a function whose value is zero for negative time and unity for positive time. Thus V_{ab} is the applied voltage for negative time and is zero for positive time indicating a sudden short circuit at time $t = 0$

By writing the voltages as in equations 32 and 33, it is inferred that only the real part of a solution involving these voltages is to be kept. Substituting them into the general constant speed relations of equations 30 and 31 and solving for the phase currents there results,

$$i_{a1} = \frac{V_s \epsilon^{j\omega t} \epsilon^{j\beta} \epsilon^{-j\pi/6}}{\sqrt{3}} \frac{1}{Z_{F1}(p + j\omega)} (1 - \mathbf{1}) \tag{34}$$

This equation is readily solved for the short-circuit current in phase a.

Tests for Short-Circuit Current

In a series of tests made by the writer, a 3 phase induction motor was connected as shown in figure 2.

The rotor was driven at some constant speed and then switch S was closed. The transient current in phase a of the rotor was recorded by an oscillograph. The curves of figure 3 show the comparison between test and calculated results. The analysis was made using the procedure already described, merely solving for the rotor currents instead of stator currents, and considering that a rotor voltage was impressed.

As another example of the use of this analysis, figure 4 indicates a comparison of test and calculated short-circuit currents for a self-excited Scherbius frequency changer. In making this analysis, it is necessary not only to include the effect of short-circuiting the stator terminals but also the effect of the transient voltage impressed on the rotor must be considered.

Appendix I—Derivation of General Equations for Stator Currents

The following equations, 15, 16, and 5, are derived in the body of the report:

$$\left.\begin{aligned} V_{ab} &= (r_1 + pL_1')(i_{a1} - i_{b1}) + \\ &\qquad pM' [\cos\theta\,(i_{a2} - i_{b2}) + \sqrt{3}\sin\theta\, i_{c2}] \\ V_{bc} &= (r_1 + pL_1')(i_{b1} - i_{c1}) + \\ &\qquad pM' [\cos\theta\,(i_{b2} - i_{c2}) + \sqrt{3}\sin\theta\, i_{a2}] \end{aligned}\right\} \tag{15}$$

$$\left.\begin{aligned} 0 &= (r_2 + pL_2')(i_{a2} - i_{b2}) + \\ &\qquad pM' [\cos\theta\,(i_{a1} - i_{b1}) - \sqrt{3}\sin\theta\, i_{c1}] \\ 0 &= (r_2 + pL_2')(i_{b2} - i_{c2}) + \\ &\qquad pM' [\cos\theta\,(i_{b1} - i_{c1}) - \sqrt{3}\sin\theta\, i_{a1}] \end{aligned}\right\} \tag{16}$$

$$\left.\begin{aligned} i_{a1} + i_{b1} + i_{c1} &= 0 \\ i_{a2} + i_{b2} + i_{c2} &= 0 \end{aligned}\right\} \tag{5}$$

For conciseness of notation the following 2 impedance functions are introduced.

$$\left.\begin{aligned} Z_1(p) &= r_1 + pL_1' \\ Z_2(p) &= r_2 + pL_2' \end{aligned}\right\} \tag{17}$$

and from equations 16 and 5

$$\left.\begin{aligned} i_{a2} - i_{b2} &= -\frac{pM'}{Z_2(p)} [\cos\theta\,(i_{a1} - i_{b1}) - \sqrt{3}\sin\theta\, i_{c1}] \\ i_{b2} - i_{c2} &= -\frac{pM'}{Z_2(p)} [\cos\theta\,(i_{b1} - i_{c1}) - \sqrt{3}\sin\theta\, i_{a1}] \\ i_{a2} + i_{b2} + i_{c2} &= 0 \end{aligned}\right\} \tag{18}$$

From equation 18:

$$i_{a2} = \frac{\begin{vmatrix} -\frac{pM'}{Z_2(p)} [\cos\theta\,(i_{a1} - i_{b1}) - \sqrt{3}\sin\theta\, i_{c1}] & -1 & 0 \\ -\frac{pM'}{Z_2(p)} [\cos\theta\,(i_{b1} - i_{c1}) - \sqrt{3}\sin\theta\, i_{a1}] & 1 & -1 \\ 0 & 1 & 1 \end{vmatrix}}{\begin{vmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ 1 & 1 & 1 \end{vmatrix}} \tag{19}$$

$$i_{a2} = -\frac{pM'}{Z_2(p)} \left[\cos\theta\, i_{a1} + \frac{1}{\sqrt{3}} \sin\theta\,(i_{b1} - i_{c1}) \right] \tag{20}$$

Similarly

$$i_{c2} = -\frac{pM'}{Z_2(p)} \left[\cos\theta\, i_{c1} + \frac{1}{\sqrt{3}} \sin\theta\,(i_{a1} - i_{b1}) \right] \tag{21}$$

Substituting equations 18, 20, and 21 into 15

$$\begin{aligned} V_{ab} = &\left\{ Z_1(p) - pM'\cos\theta \frac{pM'}{Z_2(p)}\cos\theta + pM'\sin\theta \frac{pM'}{Z_2(p)}\sin\theta \right\} \times \\ &(i_{a1} - i_{b1}) + \sqrt{3} \left\{ pM'\cos\theta \frac{pM'}{Z_2(p)}\sin\theta - \right. \\ &\left. \qquad pM'\sin\theta \frac{pM'}{Z_2(p)}\cos\theta \right\} i_{c1} \end{aligned} \tag{22}$$

$$\begin{aligned} V_{bc} = &\left\{ Z_1(p) - pM'\cos\theta \frac{pM'}{Z_2(p)}\cos\theta + pM'\sin\theta \frac{pM'}{Z_2(p)}\sin\theta \right\} \times \\ &(i_{b1} - i_{c1}) + \sqrt{3} \left\{ pM'\cos\theta \frac{pM'}{Z_2(p)}\sin\theta - \right. \\ &\left. \qquad pM'\sin\theta \frac{pM'}{Z_2(p)}\cos\theta \right\} i_{a1} \end{aligned} \tag{23}$$

References

1. Transient Conditions in Electric Machinery, W. V. Lyon. A.I.E.E. Trans., v. 42, 1923, p. 157–76.

2. Sudden Short Circuit of Alternator, Bekku. Research No. 203 of the Electrotechnical Laboratory, Tokyo, 1927.

The Determination of Circuit Recovery Rates

Actual interruption of an a-c circuit depends upon the ability of the circuit breaker to prevent the re-establishment of the arc after the current goes through zero and the arc goes out. In some circuits full voltage appears across the contacts as quickly as 40 to 80 microseconds following the current zero. This recovery rate in volts per microsecond depends upon the triple product of: the current interrupted, the normal frequency of the system, and the recovery impedance in ohms of the external circuit. The calculation of circuit recovery rates is given in this paper by presenting in curve and table form the ohmic recovery impedance, and its components, for all the practical circuits found in the field.

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THE recovery voltage rate of an a-c power circuit is the term given to the rate, in volts per microsecond, at which the voltage rises across the terminals of a circuit breaker immediately following the interruption of current by that breaker. The introduction of the knowledge of circuit breaker recovery voltages and the speed with which these voltages can appear has played an important rôle in correlating a group of seemingly unrelated phenomena regarding circuit breaker performance. Space will not permit here the enumeration of the many cases in which circuit breakers of similar design and apparently under similar conditions have behaved so differently, only to find on investigation that the respective recovery rates were different, explaining quite satisfactorily their behavior. When a breaker is reported to be having difficulty in clearing the circuit, exhibiting these difficulties by throwing oil or by producing abnormally long arc lengths, from experience it has been found that the recovery rates for the circuit attached to such a breaker are usually abnormally high. In the past, the problem has masked itself behind other seemingly unimportant details. A single breaker, for example, will appear almost human in its behavior, sometimes performing very nicely and other times exhibiting a great deal of grief. When studied, it is found that 2 or more recovery rates exist for the one breaker, the difference being due to the particular circuit connections at the time of interruption.

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In the recent purchase of the 3-cycle 287-kv impulse (piston driven oil blast) breakers for the 270 mile Boulder Dam-Los Angeles transmission line, the engineers of the bureau of power and light, city of Los Angeles, included in the breaker specifications the recovery rate which the breakers must withstand. The breaker performance was predetermined[1] from equations, developed over a period of years, employing recovery rate as one of the most important criterions for high speed circuit interruption. Completed tests on these and other impulse breakers have been quite satisfactory, which fact lends the greatest support to the correctness of the theory and design. In the summary of these tests[1] the relation between recovery rate and oil pressure stands out as the most striking and useful correlation supporting both qualitatively and quantitatively the correctness of this principle of circuit interruption.

Realizing the importance of this problem, it is the object of this paper to present a method of predetermining recovery rates and at the same time to discuss the physics or mechanics of the problem whenever necessary. The method presented herein was developed in a special effort to simplify the calculation without sacrifice of accuracy. The method will be found particularly useful in a mass determination of the recovery rates for a complete high or low voltage system, and will enable a close comparison of recovery rate for various circuits in such a system. The concept of recovery impedance has been introduced as a definite ohmic factor which defines the severity of the circuit or circuits in which the breaker is to be placed. In short, the recovery impedances for all practical circuits encountered in the field are calculated and appear in curve form in this paper. Their intelligent use will permit the rapid determination of recovery rates, the accuracy of the result being dependent upon the accuracy of the assumed circuit. These questions will be discussed below.

Recovery Voltages—Hydraulic Analogy

Imagine a large water wheel runner driving a generator under full load. Should the butterfly valve at the bottom of the penstock be suddenly closed, the velocity flow v of the penstock water of mass M would be suddenly interrupted. The stored energy in this body of water ($^1/_2Mv^2$) would no longer have its normal outlet in the load of the water wheel runner and the result would be that an enormous force F would be built up at the valve. This force would be limited only by the combined elastic properties C of the water, adjacent penstock and valve. Should this force reach such proportions as to exceed the mechanical limit of the valve, causing the valve to burst, the flow would be continued and the valve would have failed to interrupt the flow

1. For all numbered references see list at end of paper.

due to the high recovery pressure of the circuit.

Should a circuit breaker feeding a heavy d-c current be suddenly opened, the current flow I would be suddenly interrupted. The stored energy in the inductance L of the circuit ($^1/_2 LI^2$) would no longer have its normal outlet in the load of the system and the result would be that a very high voltage V would be built up at the circuit breaker terminal. This voltage would be limited only by the electrical elastance or capacitance C of the adjacent circuit. Should this voltage reach such proportions as to exceed the insulation strength of the opening breaker, causing a flashover between the contacts, the current flow I would be continued and the breaker would have failed to interrupt the current due to the high recovery voltage of the circuit.

The above analogy is not only figuratively correct but mathematically the 2 problems are the same. In the d-c circuit the problem is 2-fold, not only must the magnitude of the recovery voltage be restricted but also the rate at which this voltage appears must be kept as low as possible. In the a-c circuit, fortunately, the current passes through zero twice each cycle and normal circuit interruption occurs at such a current zero, with the result that the magnitude inherently cannot exceed twice the crest value of the normal voltage; however, the rate at which this voltage recovers is quite important, as the breaker is endeavoring to establish insulation between the contacts immediately following interruption. The criterion for satisfactory interruption, therefore, is that at all times the recovery of insulation strength exceeds the recovery of voltage to the extent that no breakdown occurs during this period to re-establish the arc.

Table I—Average Values of Circuit Constants Which Depend Upon the System and Nature of the Fault

Type of Fault	k_d	k_g	k_q	$k_0 = k_d k_g k_q$	$k = 1.028\ k_0$
One line to ground	1.0	1.0	1.0	1.0	1.028
Two line to ground	1.0	Approx. 1.73	1.0	Approx. 1.73	Approx. 1.78
Line to line	1.0	1.73	1.0	1.73	
Three phase short circuit	1.0	0.9 to 1.05	1 to 1.05	1.02	1.05
Three phase ungrounded short circuit or grounded short circuit on an ungrounded system	1.0	1.5	1.0 to 1.1	1.5	1.54

Type of Fault

The rate of rise of recovery voltage for the first phase to clear depends upon the magnitude of the normal frequency recovery voltage. Park and Skeats[2] give for the maximum voltage of the first phase to clear:

$$E_m = k_g \cdot k_d \cdot k_q \cdot E$$

where

k_g depends upon the ground conditions
k_d = decrement factor
k_q = quadrature reactance factor
E = normal phase voltage

Grouping these constants into one constant k_0, we have:

$$E_m = k_0 \cdot E$$

Table I gives the average values of these constants for various types of faults. For a more complete discussion of these constants the reader is referred to the above reference.[2]

Nomenclature

The following nomenclature will be used throughout this paper:

E = normal voltage—line to line
f = normal system frequency
ω = $2\pi f$
L = inductance which limits the short circuit current
I = root-mean-square short-circuit current in amperes
C = electrostatic capacitance
f_n = natural frequency
$\omega_n = 2\pi f_n = \dfrac{1}{\sqrt{L_n C_n}}$
rr = recovery rate in volts per microsecond
$Z_n = \sqrt{\dfrac{L_n}{C_n}}$ = impedance in ohms
Z_r = recovery impedance in ohms
k = circuit constants. (See table I.)

The maximum recovery rate is defined as "the slope of steepest line which can be drawn from the point of interruption to any point on the recovery voltage oscillations." See figures 2 and 7.

Interruption is assumed to occur at a normal current zero. The faults are assumed totally reactive; i. e., zero power factor. Only the case of a symmetrical current is considered as this gives the maximum recovery rate. No factor has been included for the decrement of the recovery voltage. This phenomena tends to reduce the recovery rate several per cent.

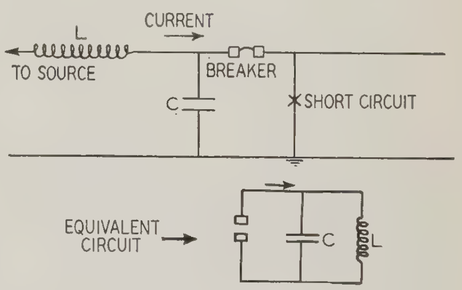


Fig. 1. A field condition which may be approximated by a single frequency equivalent circuit

Effect of Circuit Breaker

In this paper recovery rates are calculated without including any of the effects of the circuit breaker itself upon the recovery rate. This practice has been tentatively agreed to among the various manufacturers for the following reasons:

1. Inasmuch as the circuit breaker is solely a device to interrupt the circuit, regardless of how it accomplishes this feat, it would be unjust to rob the breaker of any of its qualities by imposing a recovery rate specification, which included the effect of the breaker itself. In other words, if any breaker has the property through high

electrostatic capacitance, arc drop, conducting properties after interruption, or any other incorporated scheme to reduce materially the severity of any test below the severity of the test circuit alone and in this way help to accomplish interruption, such a reduction will be credited to the breaker and the test record will state that the breaker has withstood the severity of the external test circuit.

2. This allows the recovery impedance, which is a measure of circuit severity, to become a straightforward circuit calculation independent of all the effects of the breaker.

In this connection it must be kept in mind that high recovery rate in itself can do no harm, and is only important when it allows voltages of appreciable magnitude to appear in a very short period following interruption. For this reason, in some of the double frequency cases to follow the recovery rate may appear high, but the magnitude of the voltage associated with these rates may be so low as to make them of little importance. This point will be discussed later.

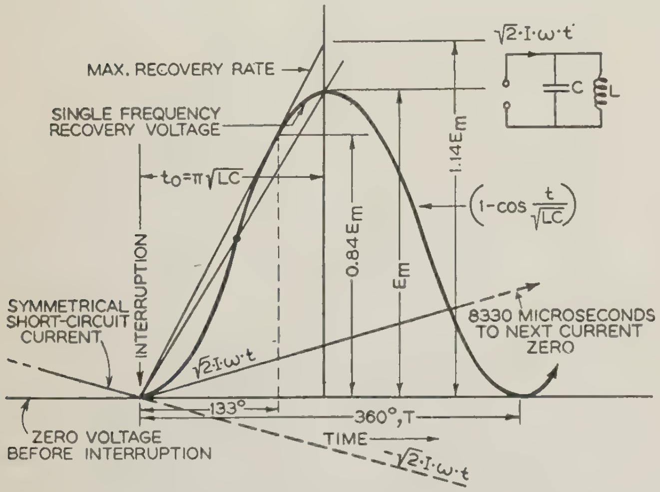


Fig. 2. Composite diagram showing the nature of the recovery voltage for the circuit of figure 1. Maximum recovery rate is shown

When L = 0.16 henrys and C = 0.01 microfarads, then t_0 = 126 microseconds

Single Frequency Recovery Voltage

In many cases the recovery voltage circuit can be represented by a single frequency circuit, as shown in figure 1. Consider the above fault to be on a 110-kv grounded 60-cycle system. With a short-circuit of 200,000 kva, the inductance limiting the current is 0.16 henrys. The symmetrical value of the short-circuit current is 1,050 amperes. An analysis of the circuit has shown that the total effective electrostatic capacitance C to ground between the circuit breaker and the current limiting inductance is about 0.01 microfarad. The equivalent circuit of this condition is shown in figure 1.

The artifice[3] employed in calculating the recovery voltage in this and all recovery rate problems (see figure 2) is to introduce at the current zero at which interruption occurs, a current equal and opposite to the short-circuit current which would have continued to flow had interruption not taken place. The resultant of these 2 currents is zero and satisfies the condition of interruption. As the only factor which is of interest is the maximum rate of rise immediately following interruption, all of which usually takes place within several hundred microseconds, the assumption that the current change during this period is linear introduces a negligible error. The current which is applied to the circuit is, therefore:

$$i = \sqrt{2}\cdot I\cdot\omega\cdot t \tag{1}$$

where

$\sqrt{2}\,I$ = crest value of the short-circuit current
$\omega = 2\pi f = 377$
t = time in seconds

It is interesting to note here that the slope of the current which generates the recovery voltage is:

$$i/t = \sqrt{2}\cdot I\cdot\omega\cdot 10^{-6} \text{ amperes per microsecond} \tag{2}$$

Introducing the current of equation 1 in the circuit of figure 1, the resultant voltage will be:

$$V_r = \sqrt{2}\cdot I\cdot\omega\cdot L(1-\cos bt) \text{ volts} \tag{3}$$

where

$$b = \frac{1}{\sqrt{LC}} \tag{4}$$

and

V_r = recovery voltage

The form of this voltage is shown in figure 2. By inspection the product $I\cdot\omega\cdot L$ is recognized as the rated root mean square voltage to ground. The crest value of the above recovery voltage is, therefore:

$$V_{r(\max)} = 2\sqrt{2}\cdot I\cdot\omega\cdot L \text{ volts} \tag{5}$$

and occurs at a time:

$$t = \pi\sqrt{LC}\,10^{6} \text{ microseconds} \tag{6}$$

Hence the rate of recovery of the *crest voltage* in this case would be:

$$rr = \left\{\frac{2\cdot\sqrt{2}\cdot I\cdot\omega\cdot L}{\pi\sqrt{LC}}\right\}10^{-6} \text{ volts per microsecond} \tag{7}$$

The maximum rate of rise for single frequency cases is 1.14 times that given by equation 7. A study of figure 2 will make this clear. Introducing this value and simplifying, there results:

$$rr = 1.028\cdot I\cdot\omega\cdot\sqrt{\frac{L}{C}}\,10^{-6} \text{ volts per microsecond} \tag{8}$$

For the above example, $k_0 = 1$, and this value is 1,630 volts per microsecond, which is a relatively high recovery rate. Properly interpreted, it says that in 93 microseconds after interruption 151,000 volts was available across the contacts in an effort to rekindle the arc and prevent interruption.

Equation 8 above is worthy of study. The circuit factor $\sqrt{\frac{L}{C}}$ appears and is here termed the recovery impedance of the circuit. It is purely ohmic in value and is that value which when multiplied by the

short-circuit current and system constants gives the recovery rate. In the above case it has a value of 4,000 ohms. The dimensional relationships between equations 8 and 2 should be closely studied.

Adopting the notation:

$$\sqrt{\frac{L}{C}} = Z_r = \text{recovery impedance in ohms} \tag{9}$$

Then the recovery rate formula becomes:

$$rr = k \cdot I \cdot \omega \cdot Z_r \cdot 10^{-6} \text{ volts per microsecond} \tag{10}$$

For values of k, see right-hand column of table I.

If all recovery rate problems dealt with the simple single frequency circuit here analyzed, the above equations might be used and this discussion would terminate at this point. Study shows that the above circuit will represent only the very simple cases, these cases usually involving only a transmission line, and except where reactors are critically located, the recovery rates are quite low. The majority of circuits which are of real interest, those in the high recovery rate class, cannot be represented by a single frequency circuit, it requiring at least a double frequency circuit to give a close approximation.

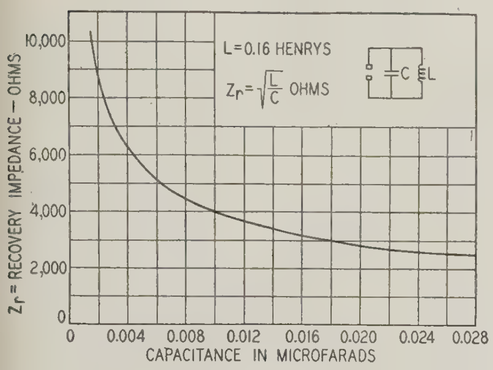


Fig. 3. Relationship between capacitance and recovery impedance for a single frequency recovery voltage

It is when attention is transferred from the single frequency circuits to the double frequency circuits, the concept of recovery impedance is found particularly adaptable. In short, it has been found that for all practical double frequency recovery voltage circuits, the recovery impedance is determinable and still retains the desirable ohmic properties that it had in the single frequency case. This allows the adoption, for all circuits, of the simple formula:

$$rr = K \cdot I \cdot \omega \cdot Z_r \cdot 10^{-6} \text{ volts per microsecond} \tag{11}$$

To the system engineer all the factors will be known except the recovery impedance and he can set about to determine this impedance for any particular circuit condition. This impedance, being expressed in ohms and ranging from 30 ohms to 10,000 ohms or higher, lends itself readily to interpretation. It is the accurate criterion for comparing one circuit with another independently of the current which is being interrupted. The recovery impedances for all double frequency circuits encountered in recovery rate problems have been calculated and appear in curve form in this paper. They will now be discussed.

Recovery Circuits—General

The major problem in accurately determining recovery rates lies in the selection of the circuit and the constants to be used. At best, the circuits given in this paper, when used for recovery rate calculations, are only approximations. They are the practical lumped circuit equivalents of the circuits connected to the breaker terminals and describe roughly the manner in which the electrostatic capacitances are distributed among the inductances of the circuit. The selection of the proper circuit to be used in any particular case and the value of the constants to be used to approximate the recovery circuit conditions is a matter of experience. No small part of this selection concerns just what parts of the circuit are important and what parts may be neglected without materially affecting the ultimate solution. A plot of the dependence of recovery impedance upon the electrostatic capacitance in the single frequency case already described is shown in figure 3. This curve shows the importance of determining the electrostatic capacitance as accurately as possible, especially when this capacitance is small.

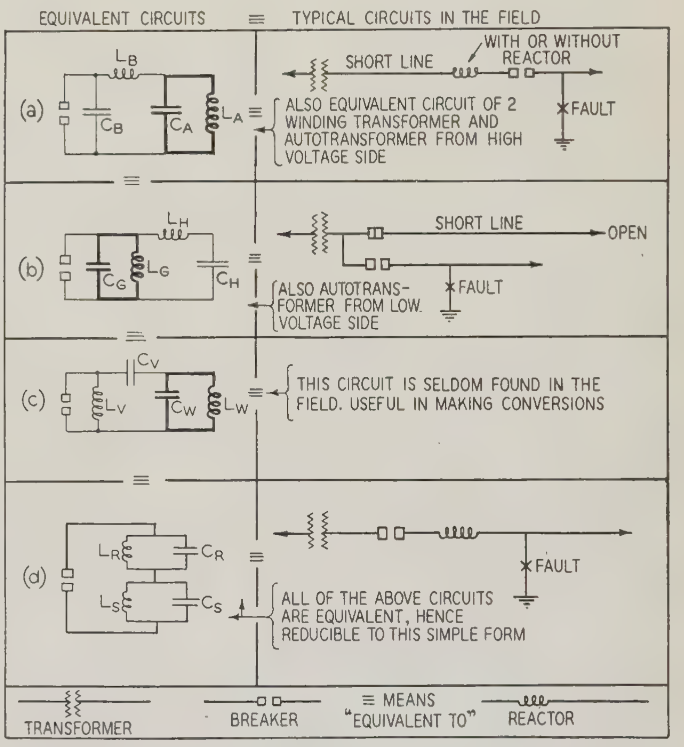


Fig. 4. Four double frequency equivalent circuits with one representative field condition. All of the above equivalent circuits are equivalent to each other and reducible to the simple form of (d)

The accumulation of data, particularly the effective electrostatic capacitances of electrical equipment, has been in progress for some time.[2,6,7] In many of the simpler cases of lines, cables, busses, bushings, reactors, etc., these constants are well known and calculations may be made readily. The major source of reliable data for the more compli-

cated equipment such as transformers and rotating equipment, especially when studied in the field, comes from the cathode ray oscillograph. These tests not only determine the particular recovery rates by actual measurement, but play an all-important part in establishing the effective constants of circuits consisting of a multiplicity of equipment. It is not within the scope of this paper to enlarge upon the problem of the circuit selection and constants, but to proceed on the assumption that these selections have been made and the approximate circuits formed. It is hoped that the calculations here presented will prove useful to the extent of creating a greater interest in a more accurate determination of these constants as related to circuit breaker performance.

Table II—Master Table Giving in Compact Form the Equivalent Relationships for Determining Frequencies, Magnitudes, and Recovery Impedance. Conversion Equations to the AB Circuit Also Appear in This Table

1. General Use: All curves may be entered with n_0 and m_0 to determine frequencies, magnitudes, or recovery impedance for all circuits shown in this table. When so used the following relations hold:

$\omega_R = \omega_B/K_S$; $L_R = J_R L_A$; Recovery Impedance $= Z_r = W_T Z_B$ (See figure 7)

$\omega_S = K_S \cdot \omega_A$; $L_S = J_S L_A$; Recovery Rate $= k \cdot I \cdot \omega \cdot Z_r\, 10^{-6}$ volts/microsecond (See text)

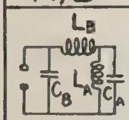
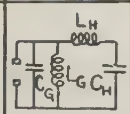
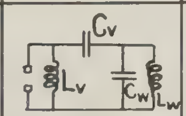
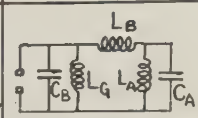
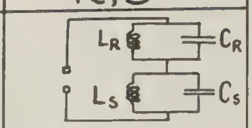
2. The frequencies of all the circuits may be determined by entering frequency curves (figure 5) with either n and m or n_0 and m_0. When so used the following relations hold:

If entered with n and m

$$\left.\begin{aligned}\omega_R &= \omega_m/K_S\\ \omega_S &= K_S \cdot \omega_n\end{aligned}\right\}\ \text{where}\quad \omega_n = \frac{1}{\sqrt{L_n C_n}},\quad \omega_m = \frac{1}{\sqrt{L_m C_m}}$$

If entered with n_0 and m_0

$$\omega_R = \omega_B/K_S \qquad \omega_S = K_S \cdot \omega_A$$

	A,B	G,H	V,W	A,B,G	R,S	GENERAL
						
$L_n =$	L_A	L_G	L_W	$\left\{\frac{L_G(L_A+L_B)}{L_G+L_A+L_B}\right\}$	L_R or L_S *	L_n
$L_m =$	L_B	L_H	L_V	$\left\{\frac{L_B(L_A+L_B)}{L_A}\right\}$	L_S or L_R	L_m
$C_m =$	C_B	C_H	C_V	$\left\{\frac{C_A L_A^2}{(L_A+L_B)^2}\right\}$	C_S or C_R	C_m
$C_n =$	C_A	C_G	C_W	C_B	C_R or C_S	C_n
$n =$	$\frac{L_B}{L_A}$	$\frac{L_H}{L_G}$	$\frac{L_V}{L_W}$	$\left\{\frac{L_B(L_A+L_B+L_G)}{L_A L_G}\right\}$	$W_R = \frac{1}{\sqrt{L_R C_R}}$	$\frac{L_m}{L_n}$
$m =$	$\frac{C_B}{C_A}$	$\frac{C_H}{C_G}$	$\frac{C_V}{C_W}$	$\frac{C_A}{C_B}\left(\frac{L_A}{L_A+L_B}\right)^2$	$W_S = \frac{1}{\sqrt{L_S C_S}}$	$\frac{C_m}{C_n}$
$n_0 =$	$\frac{L_B}{L_A}$	$\frac{L_H}{L_G}$	$\frac{L_W}{L_V}\left(1+\frac{C_W}{C_V}\right)^2$	$\frac{L_B(L_A+L_B+L_G)}{L_A L_G}$	$\left\{\frac{\sqrt{L_R L_S}(C_R+C_S)}{L_R C_R - L_S C_S}\right\}^2$ *	$\frac{L_B}{L_A}$
$m_0 =$	$\frac{C_B}{C_A}$	$\frac{C_G}{C_H\{1+n_0\}^2}$	$\frac{C_W}{C_V}\left(\frac{1}{1+n_0}\right)^2$	$\frac{C_B\left(1+\frac{L_B}{L_A}\right)^2}{C_A(1+n_0)^2}$	$\left(\frac{\sqrt{C_R C_S}\cdot(L_R+L_S)}{L_R C_R - L_S C_S}\right)^2 \frac{1}{(1+n_0)^2}$	$\frac{C_B}{C_A}$
Conversion Equations	$L_A =$	$L_G\left(\frac{L_G}{L_H+L_G}\right)$	$L_V\left(\frac{1}{1+n_0}\right)$	$L_n\left(\frac{L_n}{L_n+L_m}\right)$	$(L_R+L_S)\left(\frac{1}{1+n_0}\right)$	L_A
	$C_A =$	$C_H\left(\frac{L_H+L_G}{L_G}\right)^2$	$\frac{C_V^2}{C_V+C_W}(1+n_0)^2$	$C_m\left(\frac{L_n+L_m}{L_n}\right)^2$	$\frac{C_B}{m_0}$	C_A
	$L_B =$	$L_H\left(\frac{L_G}{L_H+L_G}\right)$	$L_V\left(\frac{n_0}{1+n_0}\right)$	$L_m\left(\frac{L_n}{L_n+L_m}\right)$	$n_0 L_A$	L_B
	$C_B =$	C_G	$\left(\frac{C_V C_W}{C_V+C_W}\right)$	C_n	$\left(\frac{C_R C_S}{C_R+C_S}\right)$	C_B
$Z_A =$	$\sqrt{\frac{L_A}{C_A}}$	$\sqrt{\frac{L_G}{C_H}\left(\frac{L_G}{L_H+L_G}\right)^3}$	$\sqrt{\frac{L_A}{C_A}}$	$\sqrt{\frac{L_n}{C_m}\left(\frac{L_n}{L_n+L_m}\right)^3}$	$\sqrt{\frac{L_A}{C_A}}$	$\sqrt{\frac{L_A}{C_A}}$
$Z_B =$	$\sqrt{\frac{L_B}{C_B}}$	$\sqrt{\frac{L_H}{C_G}\left(\frac{L_G}{L_H+L_G}\right)}$	$\sqrt{\frac{L_B}{C_B}}$	$\sqrt{\frac{L_m}{C_n}\left(\frac{L_n}{L_n+L_m}\right)}$	$\sqrt{\frac{L_B}{C_B}}$	$\sqrt{\frac{L_B}{C_B}}$
$W_A =$	$\frac{1}{\sqrt{L_A C_A}}$	$\frac{1}{\sqrt{C_H(L_H+L_G)}}$	$\sqrt{\frac{(C_V+C_W)}{L_V C_V^2(1+n_0)}}$	$\frac{1}{\sqrt{C_m(L_m+L_n)}}$	$\frac{1}{\sqrt{L_A C_A}}$ or $= \frac{1}{\sqrt{L_n C_n}}$	$\frac{1}{\sqrt{L_A C_A}}$
$W_B =$	$\frac{1}{\sqrt{L_B C_B}}$	$\sqrt{\frac{(L_H+L_G)}{L_H L_G C_G}}$	$\frac{1}{\sqrt{L_B \cdot C_B}}$	$\sqrt{\frac{(L_n+L_m)}{L_m \cdot L_n \cdot C_n}}$	$\frac{1}{\sqrt{L_B C_B}}$ or $= \frac{1}{\sqrt{L_m C_m}}$	$\frac{1}{\sqrt{L_B C_B}}$

* Values so chosen that $L_R \cdot C_R$ is greater than $L_S \cdot C_S$. When $L_R C_R = L_S C_S$ use special equations in appendix.

Double Frequency Circuits

The vast majority of recovery circuits which cannot be approximated by the single frequency circuit of figure 1 can be approximated by 1 of the 4 double frequency circuits of figure 4. These equivalent circuits comprise all the possible 4-parameter double-frequency circuits (neglecting resistance) which will be encountered in the study of recovery rates. They comprise one class, all having in common a final through inductance path from the breaker terminals uninterrupted by capacitance necessary for the flow of current; as well as an initial through capacitance path from the breaker terminals uninterrupted by inductance which is imperative to the nature of the phenomena. Each of these circuits contain the simple coupled parameters of figure 1 (as shown in heavy lines) and for study these parameters in all circuits will be given the subscript *n*. Thus:

$$L_n = L_A, L_G, L_W, L_R \tag{12}$$

$$C_n = C_A, C_G, C_W, C_R \tag{13}$$

The 2 remaining parameters will be given the subscript *m*. Thus:

$$L_m = L_B, L_H, L_V, L_S \tag{14}$$

$$C_m = C_B, C_H, C_V, C_S \tag{15}$$

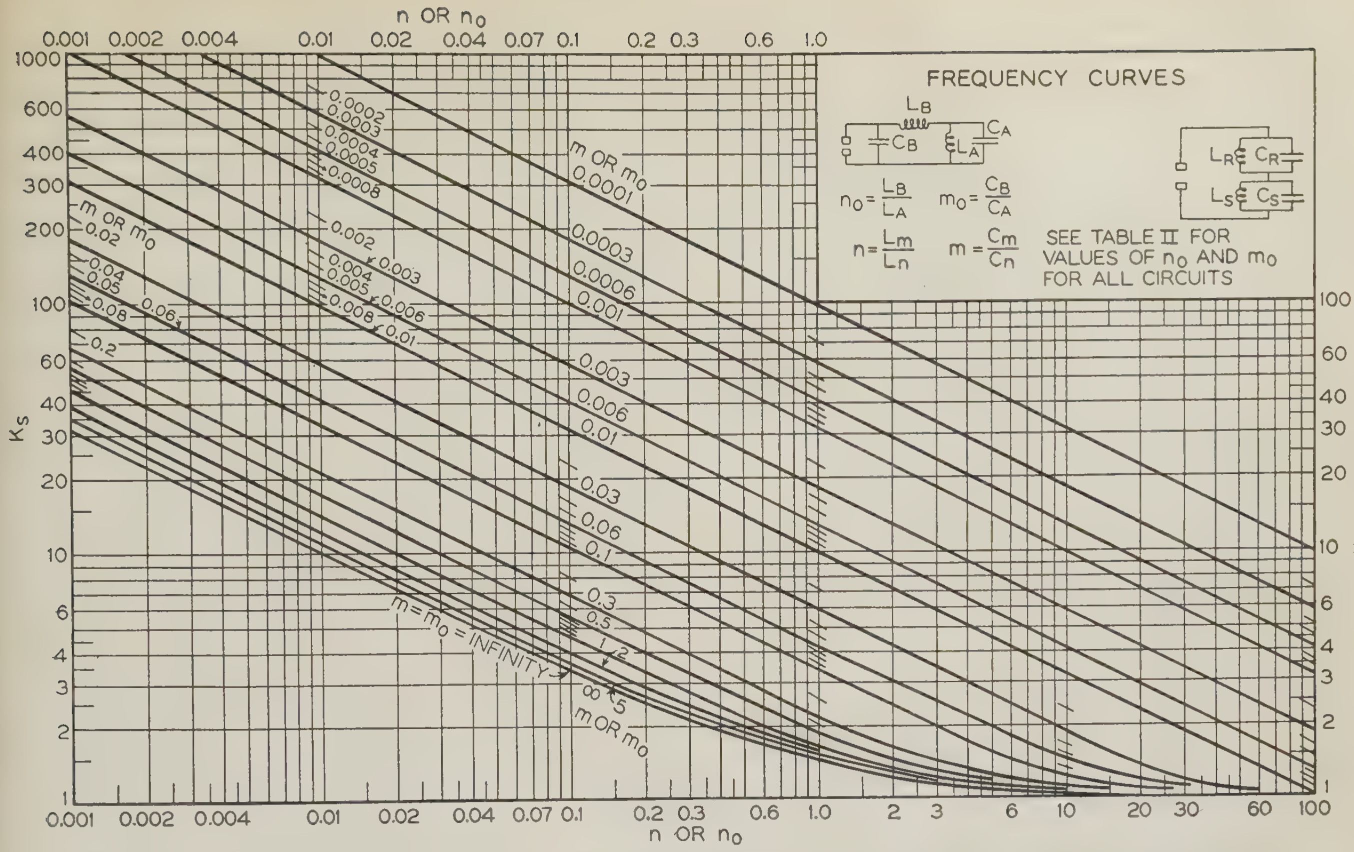


Fig. 5. Frequency curves for the purpose of determining the frequencies of any of the circuits of table II

If entered with n and m

$\omega_S = K_S\omega_n$
$\omega_R = \omega_m/K_S$

If entered with n_0 and m_0

$\omega_S = K_S\omega_A$
$\omega_R = \omega_B/K_S$

$$\omega_R = \frac{1}{\sqrt{L_RC_R}};\ \omega_A = \frac{1}{\sqrt{L_AC_A}};\ \omega_n = \frac{1}{\sqrt{L_nC_n}}$$

$$\omega_S = \frac{1}{\sqrt{L_SC_S}};\ \omega_B = \frac{1}{\sqrt{L_BC_B}};\ \omega_m = \frac{1}{\sqrt{L_mC_m}}$$

Now these 4 circuits, although all different, may be made equivalent to each or any of the other 3 circuits by the simple transformation of constants. (See reference 5, and appendix to present paper.) This fact is of great value, as they all may be transformed into the simple form R, S (figure 4*d*) which by inspection has the 2 frequencies isolated. It follows from equation 3 that the recovery voltage for this circuit will be:

$$V_r = k \cdot I \cdot \omega\{L_R(1 - \cos \omega_R t) + L_S(1 - \cos \omega_S t)\} \tag{16}$$

Here the frequencies and magnitude are both immediately available. They are:

$$f_R = \frac{1}{2\pi\sqrt{L_RC_R}} \qquad f_S = \frac{1}{2\pi\sqrt{L_SC_S}} \qquad (17)\ (18)$$

Per unit amplitude of $f_R = L_R/L_R + L_S$ (19)

Per unit amplitude of $f_S = L_S/L_R + L_S$ (20)

It follows that due to the unrestricted equivalence of all of the circuits of figure 4, the above equations enable the determination of the frequencies and magnitudes, and hence the recovery impedance of each of the circuits provided they in turn are converted into the form of figure 4*d*. The labor of these conversions, however, has been considerably condensed in presenting table II. *Here in simple arithmetical form are all the relationships required to determine the frequencies, magnitudes, or recovery impedances for all of the circuits of figure 4.* The use of table II is perfectly straightforward and will be outlined here:

1. Having formed the particular circuit approximation suggested in figure 4;

2. Determine n_0 and m_0 from table II for the particular circuit chosen.

3. (*a*) To determine frequencies enter the curves of figure 5 with n_0 and m_0 determining K_S. Then:

$\omega_R = \omega_B/K_S$ and $\omega_S = K_S\omega_A$; where $\omega_N = 2\pi f_N$

(*b*) To determine the magnitudes of the above frequencies enter the curves of figure 6 with n_0 and m_0 determining J_R and J_S. Then:

$L_R = J_RL_A$ and $L_S = J_SL_A$ (Note: $J_R + J_S = n_0 + 1$)

(*c*) To determine recovery impedance Z_R directly, enter the curves of figure 7 with n_0 and m_0 determining W_T. Then:

$Z_R = W_TZ_B$ or ($Z_R = Z_A$ in some cases. See figure 7)

4. In all of which:

n_0, m_0, ω_B, ω_A, L_A, Z_B, and Z_A are determined from table II for the particular circuit under consideration.

Hence to determine the recovery impedance of any of the circuits of table II requires, at most, the arithmetical computation of n_0, m_0, and Z_B and reading one value, W_T, from the curves of figure 7. *In doing this actually the following operations are being performed automatically:*

1. The circuit chosen is converted by means of the conversion equations of table II into the form A, B of table II, chosen as the base circuit because of its frequent occurrence.

2. This new A, B circuit is then converted into the simple form R, S by means of the computed transformation curves of figure 5 and figure 6.

3. The 2 frequencies f_R and f_S so determined are plotted in (1 − cos) form at their respective amplitudes L_R and L_S and added as indicated by equation 16, and shown graphically in figure 7.

4. The maximum slope is then drawn from the origin to this composite recovery voltage, as indicated at the bottom of figure 7, and this slope is the recovery impedance in ohms Z_r determined from the product of W_T and Z_B as computed above. *A study of the above operations will suggest to the reader the possibility of performing the separate operations, all or any of which are made readily available here for the solutions of special cases.*

In table II will be found complete conversion equations to the A, B circuit. Quite often in circuit reductions and simplifications conversion relationships to the G, H and V, W circuits are necessary. These are given in tables III and IV.

As previously mentioned, the recovery impedance as determined above includes the high frequency oscillations which may be of very low amplitude. Hence, it is desirable, where complete information is desired, to check the relative amplitudes from figure 6. On these curves will be found a line drawn which is 40 per cent of the total amplitude of $(J_R + J_S)$. Amplitudes below this line indicate that the magnitude of that frequency is less than 80 per cent of the normal voltage crest, this value being tentatively set up as a dividing line. Special curve sheets can be made easily which give the recovery impedance automatically neglecting the high frequency oscillations below any desired percentage of the normal crest voltage. Space here does not permit this extension of the above curves.

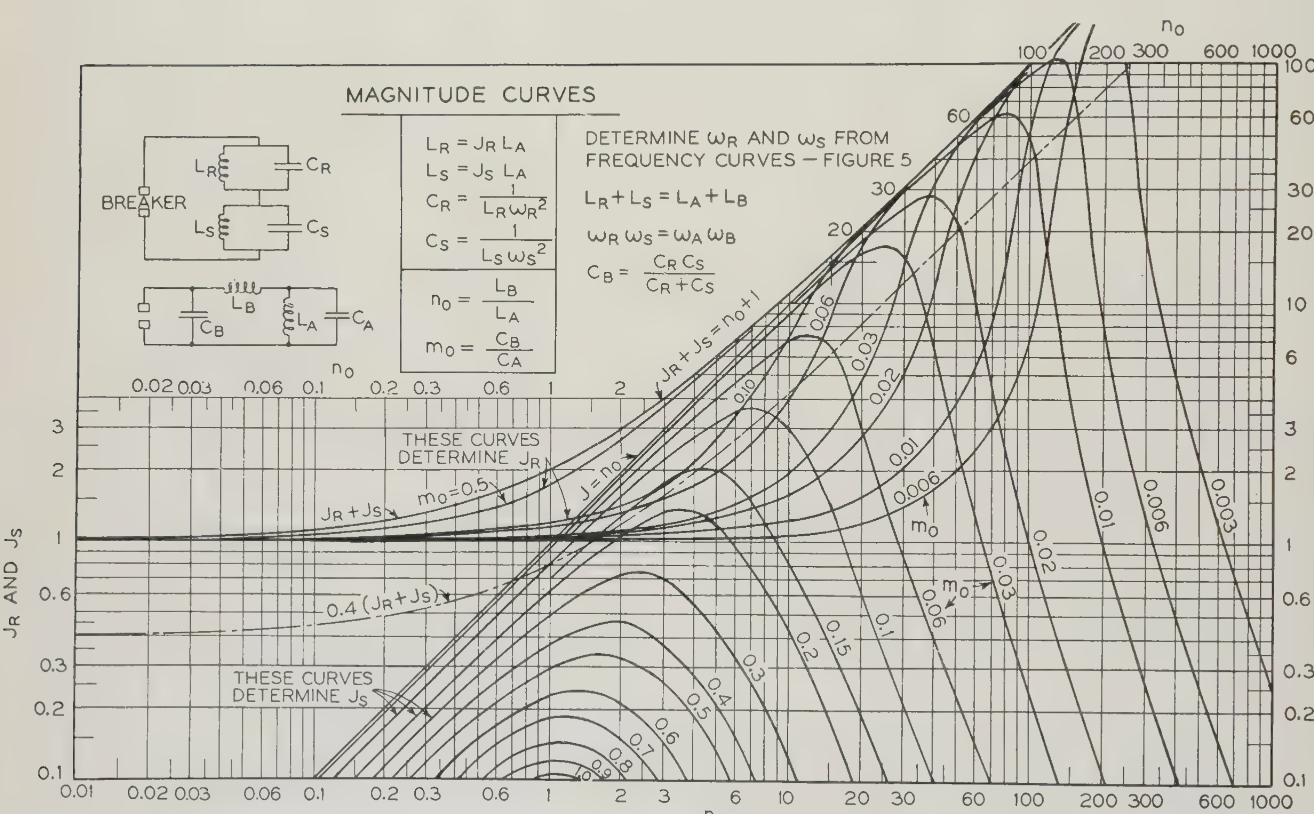


Fig. 6. Magnitude curves for the purpose of determining the magnitudes of the frequencies of figure 5

Five Parameter Circuits

In the determination of recovery rates of field conditions, quite often 5 parameter circuits are encountered which require solution. Some of these circuits are shown in figure 8, all of which have only 2 frequencies and may be reduced on inspection to any of the circuits of figure 4. For example, a is the most common of these circuits and is reduced as follows:

Separate the circuit as shown on the left of figure 9. The right-hand side of this circuit is recognized as the A, B circuit. Transform this circuit to the G, H circuit by means of table III. Recombine with the left-hand side adding the 2 inductances in parallel. The result will then be a new G, H circuit which may be transformed into any of the other circuits as desired. The above 5 parameter circuit is found so frequently that it has been given a place on the master table, II, thus eliminating the necessity of the above transformations for this particular circuit. Frequencies, magnitudes, and recovery impedance can be determined rapidly for this circuit as outlined for all circuits of table II. In a similar way the other circuits of figure 8 may be reduced to simpler forms; their infrequent occurrence does not justify their development here.

Reversibility

It will only be mentioned here that all of the above processes are quite reversible. That is, having

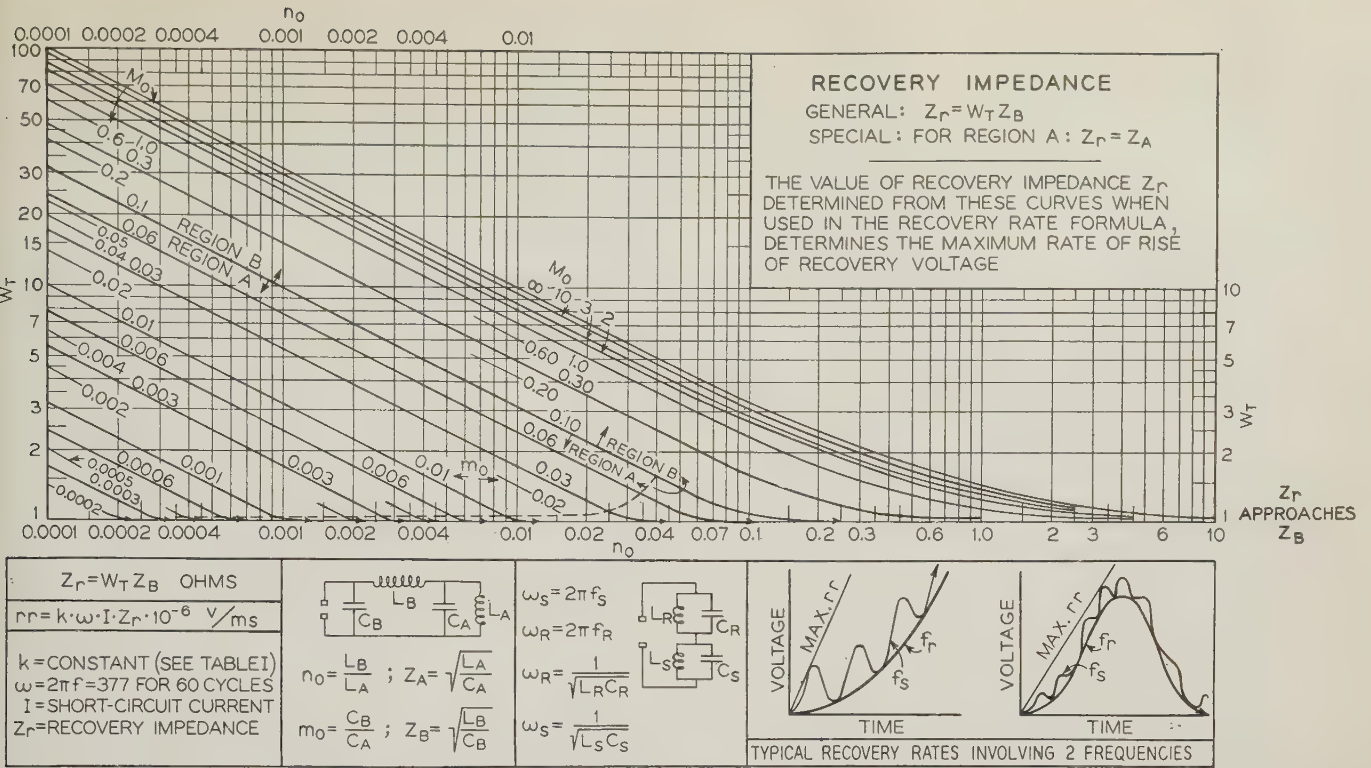


Fig. 7. Recovery impedance curves for all the circuits of table II. These curves determine Z_r of the recovery rate formula

a cathode ray oscillogram from which 2 frequencies and magnitudes can be determined, and knowing the circuit and power conditions under which the film was taken, the equivalent lumped circuits which will reproduce the film may be determined by means of the equations and curves given in this paper.

One of the practical uses of this reversibility is the development of lumped double frequency circuits to approximate the transformer. It is known that transformers when oscillating at their natural frequencies exhibit many frequencies. Quite often transformers may be represented, as far as recovery rates are concerned, by a single frequency. In the majority of cases, however, greater accuracy will be obtained by representing the transformer by one of the double frequency circuits of table II. Greater accuracy than this is not warranted because the rate of change of current in the recovery rate problem is usually not sufficient to excite higher transformer frequencies, and if excited their amplitude would be so low that they should be neglected. For general use, however, a knowledge only of the recovery impedance of a transformer or any apparatus is not sufficient because in the field setting the recovery circuit must be formed, including lines, cables, reactors, bushings, busses, transformers, etc., and hence each component element must be expressed in equivalent circuit form so that the approximate field circuit can be assembled as accurately as possible. (Recovery impedances cannot be added in series or in parallel except in very special cases.) The use of the double frequency circuit analysis in this paper will prove useful in the development of the equivalent circuits of the more complicated apparatus.

In general, the highest recovery rates are associated with transformers, not because the recovery impedances are highest, but because the power concentrations are high, combined with moderately high recovery impedances. In terms of equation 11, the product $I{\cdot}Z_r$ is maximum. Higher recovery impedances are associated with some of the current limiting devices, but inherently due to the restricted current, the product $I{\cdot}Z_r$ is smaller. The use of resistors shunting current limiting reactors, will considerably reduce the recovery impedance associated with reactors, especially when connected close to the breaker which must interrupt the circuit. The recovery impedances of shielded transformers will be found beneficially smaller due to the higher internal capacitance. Capacitors recommended for lightning protection also can be very effectively employed in reducing the recovery impedance of the circuit in which they are located. The electrostatic capacitance of metal clad bus structure, cables, and coupling capacitors are all beneficial to breaker performance especially when they provide the major capacitance paths close to the breaker terminals.

Transmission Lines and Machine Windings

When the only recovery circuit connected to a breaker is a long transmission line, the recovery impedance of the circuit is equal to the surge impedance of the line. This is the well-known $\sqrt{\frac{L}{C}}$ value of the line. The above is true provided the line is so long that the first or subsequent reflections do not affect the maximum recovery rate calculated on this basis. If the line is short, several

Table III—Conversion Equations to the G, H Circuit

G, H	A, B	V, W	R, S
L_H	$L_B\left\{\frac{L_A+L_B}{L_A}\right\}$	$L_W\left\{\frac{C_V+C_W}{C_V}\right\}^2$	$\frac{L_R L_S (L_R+L_S)(C_R+C_S)^2}{(L_R C_R - L_S C_S)^2}$
L_G	(L_A+L_B)	L_V	(L_R+L_S)
C_H	$C_A\left\{\frac{L_A}{L_A+L_B}\right\}^2$	$\frac{C_V^2}{C_V+C_W}$	$\frac{(L_R C_R - L_S C_S)^2}{(L_R+L_S)^2 \cdot (C_R+C_S)}$
C_G	C_B	$\frac{C_V \cdot C_W}{C_V+C_W}$	$\frac{C_R \cdot C_S}{C_R+C_S}$

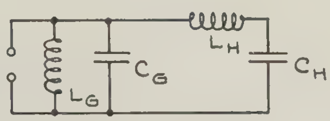
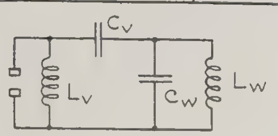


Table IV—Conversion Equations to the V, W Circuit

V,W	G, H	A, B	R, S
L_V	L_G	(L_A+L_B)	(L_R+L_S)
L_W	$L_H\left\{\frac{C_H}{C_G+C_H}\right\}^2$	$\frac{L_A^3 C_A^2 L_B L_V}{(L_A^2 C_A + L_V^2 C_B)^2}$	$\frac{L_{RS} \cdot C_R \cdot C_S}{C_V \cdot C_W}$ Where $L_{RS} = \left(\frac{L_R \cdot L_S}{L_R+L_S}\right)$
C_V	(C_H+C_G)	$\left\{\frac{C_A \cdot L_A^2}{L_V^2}\right\} + C_B$	$\frac{(L_R C_R + L_S C_S) - L_{RS}(C_R+C_S)}{(L_R+L_S)}$
C_W	$\frac{C_G}{C_H}(C_H+C_G)$	$C_B + \left(\frac{C_B^2 \cdot L_V^2}{C_A \cdot L_A^2}\right)$	$\frac{C_{RS} \cdot C_V}{C_V - C_{RS}}$ Where $C_{RS} = \left(\frac{C_R \cdot C_S}{C_R+C_S}\right)$



reflections must be included or approximated by using the π equivalent of a short line.

When, in addition to a single or a double frequency recovery circuit, there exists an additional long transmission line attached to the circuit at the breaker, the recovery circuit will be altered by having in parallel across the breaker terminals a resistance equal to the surge impedance of the appended line. The presence of a long line connected at the breaker will, in general, cause the

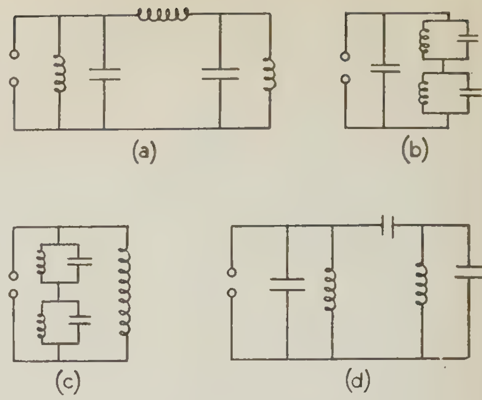


Fig. 8. Some 5-parameter double-frequency circuits all of which are reducible (as shown in figure 9) to one of the equivalent circuits of figure 4

recovery impedance to be so low that a complete analysis is unnecessary. Although the recovery impedance of the circuit, without the line so connected, cannot be added in parallel to the surge impedance of the line to form the final recovery impedance, the value so obtained will be found to be pessimistically higher than the value obtained by a rigorous analysis.

As generator and motor windings have been shown to behave as transmission lines to such transients,[7] their surge impedances determine their recovery impedances, subject to the same laws of reflections as mentioned above for short lines. If the machine windings have been made nonoscillatory[7] (no neutral reflections) by properly grounding through a neutral impedance they may be considered as long lines of the same surge impedance.

The lowest recovery impedances encountered are those of long cables connected to the breaker. Here the recovery impedance ranges from 30 to 70 ohms.

Summary

Circuit recovery impedance has been introduced as a true measure of circuit severity. It is an ohmic impedance Z_r dependent upon the external circuit, independent of the breaker. The maximum rate of change of current in amperes per microsecond at the moment of interruption of a short circuit at a normal current zero is dependent upon the type of fault, the steady-state short-circuit current and normal frequency ($k \cdot I \cdot \omega \cdot 10^{-6}$). From Ohm's law, the product of amperes per microsecond and recovery impedance in ohms is volts per microsecond, which is defined as recovery rate:

$$rr = k \cdot I \cdot \omega \cdot Z_r \cdot 10^{-6} \text{ volts per microsecond} \qquad (11)$$

For a single frequency circuit this ohmic recovery impedance is $\sqrt{\frac{L}{C}}$, but in more complicated double frequency circuits the recovery impedance, although still ohmic, is dependent upon 4 factors: the 2 frequencies and their corresponding magnitudes. The determination of these 4 factors as well as the direct determination of recovery impedance have been given in curve and table form for all the practical double frequency circuits which will be encountered in the field.

The flexibility of these circuits and their analysis have been indicated by extending their use to some 5 parameter double frequency circuits often found in recovery rate studies. Their use for the purpose of determining the approximate equivalent circuits of transformers, for recovery rate purposes, has been indicated.

It is felt that the introduction of the concept of recovery impedance as a single ohmic factor and the most important element in the recovery rate equation, together with a rapid means of its accurate determination will help the field engineer further to correlate recovery rate with breaker performance and to lead ultimately to its adoption as one of the factors which determine the rating of a circuit breaker.

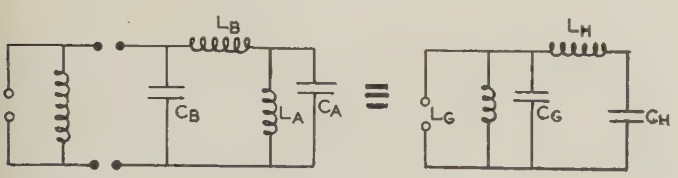


Fig. 9. Showing how figure 8(a) is reduced by means of table III to the 4 parameter, G, H circuit of figure 4

Appendix

It is the purpose of this appendix to present the basic equations which prove the equivalence of the circuits of figure 4 and suggest the method of calculation of the curves of figures 5, 6, and 7.

All the circuits of figure 4 contain one pure pair of coupled parameters as designated by the heavy lines. Giving these parameters the subscript n, there results:

$$L_n = L_A, L_G, L_W, L_R \tag{12}$$

$$C_n = C_A, C_G, C_W, C_R \tag{13}$$

The 2 remaining parameters take the subscript m, thus:

$$L_m = L_B, L_H, L_V, L_S \tag{14}$$

$$C_m = C_B, C_H, C_V, C_S \tag{15}$$

Now let:

$$n = \frac{L_m}{L_n} \quad \text{and} \quad m = \frac{C_m}{C_n} \qquad (21)\ (22)$$

$$M_{nm} = L_n \cdot L_m \cdot C_n \cdot C_m \tag{23}$$

$$N_{nm} = L_n \cdot C_n + L_m \cdot C_m + L_n \cdot C_m \tag{24}$$

(The product $L_n \cdot C_m$ occurs only when these parameters are coupled in any manner. Hence, as no coupling exists between L_R and C_S:

$$N_{RS} = L_R C_R + L_S C_S \tag{25}$$

$$Q_{nm} = \sqrt{N^2_{nm} - 4M_{nm}} \tag{26}$$

L_∞ = the impedance of the circuit if all the capacitances were removed (open circuited). Thus:

$$L_\infty = (L_A + L_B), L_G, L_V, (L_R + L_S) \tag{27}$$

C_0 = the impedance of the circuit if all the inductances were removed (open circuited). Thus:

$$C_0 = C_B, C_G, \left(\frac{C_V C_W}{C_V + C_W}\right), \left(\frac{C_R C_S}{C_R + C_S}\right) \tag{28}$$

$$C_{nm}' = \frac{M_{nm}}{C_0} \tag{29}$$

The differential equation of each of the circuits of figure 4 is similar in form and the solution of these equations shows that the operational impedance Z_p may be expressed by the following equation:

$$Z_{(p)} = \left(\frac{L_\infty p + C' p^3}{M p^4 + N p^2 + 1}\right) 1 \tag{30}$$

The following relations are then obtained by equating the respective coefficients:

$$M = M_{AB} = M_{GH} = M_{VW} = M_{RS} \tag{31}$$

$$N = N_{AB} = N_{GH} = N_{VW} = N_{RS} \tag{32}$$

$$\therefore \quad Q = Q_{AB} = Q_{GH} = Q_{VW} = Q_{RS} \tag{33}$$

$$L_\infty = (L_A + L_B) = L_G = L_V = (L_R + L_S) \tag{34}$$

$$C_0 = C_B = C_G = \left(\frac{C_V C_W}{C_V + C_W}\right) = \left(\frac{C_R C_S}{C_R + C_S}\right) \tag{35}$$

From these relations tables II, III, IV were compiled.

The curves of figures 5, 6, and 7 were determined from the following relations:

Let:

$$N_R = (N - Q), \tag{36}$$

$$N_S = (N + Q), \tag{37}$$

$$\omega_R^2 = \left(\frac{N_R}{2M}\right) \tag{38}$$

$$\omega_S^2 = \left(\frac{N_S}{2M}\right) \tag{39}$$

Then:

$$L_R = \left\{\frac{2L_\infty C_0 - N_R}{2C_0 Q \omega_R^2}\right\} = \frac{1}{C_R \omega_R^2} \tag{40}$$

$$L_S = \left\{\frac{N_S - 2L_\infty C_0}{2C_0 Q \omega_S^2}\right\} = \frac{1}{C_S \omega_S^2} \tag{41}$$

$$C_R = \left\{\frac{2C_0 Q}{2L_\infty C_0 - N_R}\right\} = \frac{1}{L_R \omega_R^2} \tag{42}$$

$$C_S = \left\{\frac{2C_0 Q}{N_S - 2L_\infty C_0}\right\} = \frac{1}{L_S \omega_S^2} \tag{43}$$

The above 4 equations are general for all of the circuits of figure 4. Their presentation in curve form was made possible by introducing the ratios n and m. Hence, for example:

$$K_S = \sqrt{\frac{q - \sqrt{q^2 - 4mn}}{2mn}} \qquad \text{(See figure 5)} \tag{44}$$

where

$$q = (1 + mn + m) \tag{45}$$

$$n = \left(\frac{L_m}{L_n}\right) \quad \text{and} \quad m = \left(\frac{C_m}{C_n}\right) \qquad (21)\ (22)$$

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Capacitive Excitation for Induction Generators

Up to the present, applications of induction generators have been limited, mainly because they must be paralleled with an existing synchronous system to determine their frequency and voltage and to obtain their necessary excitation. The tests described in this paper show that an induction machine may be operated as an independent or isolated generator at a predetermined voltage and frequency, with excellent wave form, by means of capacitive excitation. Further, proper choice and arrangement of the capacitors will result in a practically flat external load-voltage characteristic.

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THE DRIVING of an induction motor faster than synchronous speed causing it to generate alternating current power is quite well understood. Some installations of induction machines operated in this manner have been made, but as yet the practice of using induction generators has not been adopted to any appreciable extent. Probably the chief reason for this is that the induction machine must draw a lagging magnetizing current which up to this time has been supplied by the synchronous machinery of the system to which it is connected. This fact and the fact that the voltage and frequency of the induction generator are dependent entirely upon that of the connected system are the main disadvantages of the induction machine acting as a generator. Among the advantages may be listed the characteristic mechanical strength and ruggedness of the induction machine, decrease in station sustained short-circuit risk, the ability to run at high speeds, and relatively low initial and upkeep costs.

The purpose of this paper is to show that an induction machine can be made to operate as an isolated or independent generator, incorporating all the foregoing advantages and omitting most of the main disadvantages, by supplying the exciting or magnetizing current from static capacitance connected in shunt across the terminals of the machine. The following conclusions seem warranted:

1. The induction machine with capacitive excitation will build up its voltage exactly as does a d-c shunt generator, the final build-up value being determined by the saturation curve of the machine and by the value of reactance of the excitation capacitance.

2. Wave shape of the induction generator with capacitive excitation is sinusoidal.

3. Frequency of the output is directly proportional to the rotor speed minus the slip speed.

4. Machine constants can be compensated for quite well by means of series capacitance in the lines, resulting in a fairly flat external characteristic under unity power factor load conditions.

5. The induction generator can be made to handle almost any type of load, provided that the loads are compensated to present unity power factor characteristics to the generator.

6. Use of the induction generator with capacitive excitation may be made: (a) in laboratories where a source of sine wave power is desired; and (b) in installations of small capacity where single or 3 phase power is required, and where the cost of a synchronous generator and auxiliaries is prohibitive.

7. Present low cost of capacitors makes possible comparatively cheap installations, especially those of small capacity.

8. Small series capacitive reactances required for "compounding" can be obtained by means of series transformers with the capacitors connected to the high voltage sides of these transformers.

Build-Up of Generator Voltage

The build-up of voltage of the d-c shunt generator is known to depend upon residual magnetism in the field poles of the machine and upon the resistance of the field circuit, the final build-up voltage being determined by the field circuit resistance. It has been discovered that the induction generator with static capacitance connected in shunt across its terminals will build up its voltage in a manner similar to the build-up of the d-c shunt generator. Residual magnetism in the iron of the magnetic circuit sets up a small alternating voltage in the stator; this voltage applied to the capacitance causes a lagging magnetizing current to flow in the stator windings (machine applies leading quadrature current to the capacitance, or draws a lagging quadrature current). If the capacitance is of the proper value, the current that can flow will be large enough to increase the flux existing in the air gap. An increase of the air gap flux will result in a higher voltage, larger exciting current drawn by the capacitance, more air gap flux, and so on until the terminal voltage of the machine reaches its final build-up value. This value is determined by the saturation curve of the machine and by the capacitive reactance of the connected capacitance.

Following is an analysis of the build-up of the induction generator with capacitive excitation: If both the saturation curve (terminal no-load voltage versus exciting current) and a straight line through the origin, the slope of which is the capacitive reactance X_c, are plotted to the same scales, the point where the straight line intersects the saturation curve is the final build-up point. This corresponds identically to the behavior of the d-c shunt generator

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for which, if the saturation curve of the machine is known, the final build-up voltage for any particular field resistance can be predetermined by plotting on the same sheet and to the same scales the saturation curve and the field resistance, $R_f = E/I_f$. The point where the straight line, the slope of which is R_f, intersects the saturation curve is the point where the voltage will cease to build up. In like manner, if the saturation curve of the induction generator is known, the final build-up voltage for any particular capacitive reactance can be predetermined as shown in figure 1. The results given here as well as every point on the curve check almost perfectly with the measured values shown as encircled points on the saturation curve. This close agreement of measured and calculated values gives assurance that the theory of build-up as outlined is essentially correct. It may be seen also from the d-c analogy that the capacitive reactance of the induction generator corresponds to the field circuit resistance of the d-c shunt generator. The curve of figure 1 is for 3 phase operation. Similar results have been obtained for single phase operation where excitation is obtained from capacitance connected across 2 terminals of the machine.

An important part of the foregoing discussion centers around the saturation curve of the induction generator. This can be obtained in either of 2 ways: (1) by exciting the machine from a separate source of variable voltage of good wave form, keeping the power transfer zero between the machine and the source of excitation; or (2) by adjustment of the capacitive reactance, which gives a set of values on the workable portion of the curve. The results of these 2 widely different methods give practically the same saturation curve.

Frequency

The frequency of the induction generator is directly proportional to the actual speed of the rotor minus the slip speed. At no load, when the slip is practically negligible, the frequency is directly proportional to speed. Experimental results show this to be true. However, since the slip of the induction

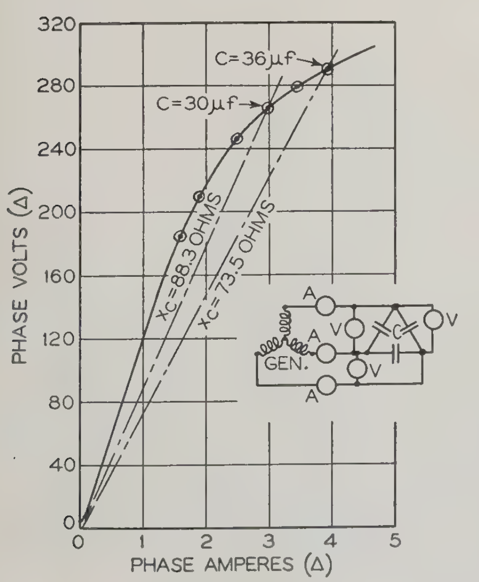


Fig. 1. No-load saturation curve and final build-up voltages of a 3-phase 60-cycle 220-volt 5-horsepower induction generator with capacitive excitation

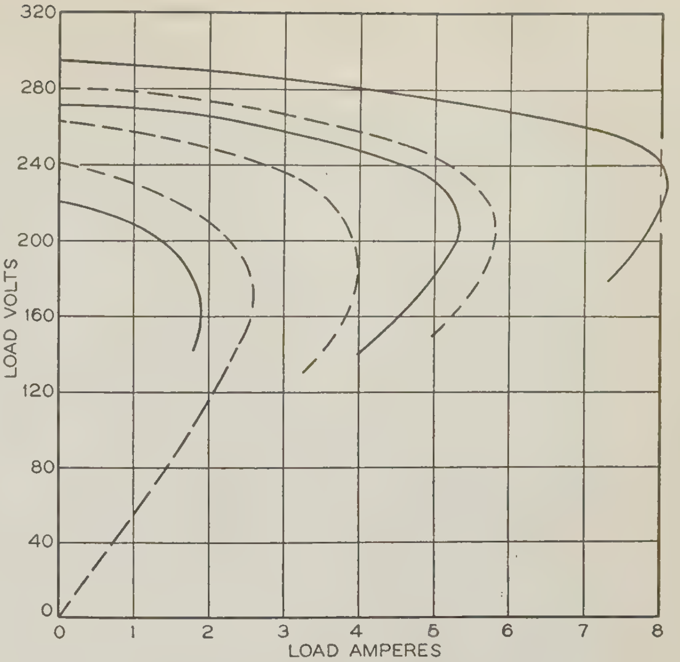


Fig. 2. External load-voltage characteristics of machine of figure 1 with unity power factor load

Solid lines are for 3 phase operation; dashed lines for single phase operation

generator increases with increasing load, it is seen that in order to maintain constant frequency, the speed of the rotor must be increased by an amount equal to the slip speed. If constant frequency is desired—as it generally is—the induction generator must be driven by a prime mover the speed of which increases with load.

Wave Shape of Induction Generator Voltage

In the calculation of X_c, the capacitive reactance used in the results of figure 1, the frequency was held constant at 60 cycles and it was assumed that the voltage wave was of sinusoidal form. The results obtained by these calculations checked very closely with the measured results, giving confirmation of the sine wave assumption. An oscillogram of the voltage wave gave conclusive proof that the assumption was correct and that the voltage wave was actually a sine wave. This fact is perhaps of considerable importance. Heretofore, a sine wave machine was obtained as a result of much arduous labor and the solution of many complicated design problems; now a sine wave voltage can be obtained easily from an ordinary induction motor by the use of capacitive excitation. This fact may open a new field for the induction machine, especially for laboratory use where a sine wave voltage sometimes is required, and where the cost of a synchronous machine of proper design is prohibitive.

Capacitive excitation was tried on 2 different induction machines: One was a General Electric 5-horsepower 3-phase induction motor having a squirrel-cage rotor with closed slots; the other was a Westinghouse 5-horsepower 3-phase motor, of older design having a regular squirrel-cage rotor with open slots. These machines built up their voltages

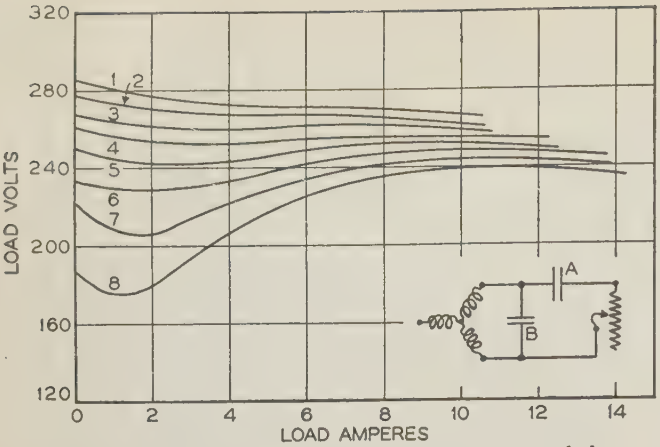


Fig. 3. External load-voltage characteristics of the machine of figure 1, "compounded" by inserting capacitance in series with the load

Capacitance A was fixed at 192 microfarads; capacitance B was varied as follows:

Curve	Microfarads	Curve	Microfarads
1	84	5	72
2	81	6	69
3	78	7	66
4	75	8	63

as already described, and gave a sine wave voltage when operated both as 3 phase and as single phase machines.

To determine the effect of capacitive excitation on the wave shape of a synchronous generator, a synchronous salient-pole 3-phase 6.3-kva generator, having a flat topped voltage wave was subjected to a capacitive load. With no d-c field on the generator, it was found that when the capacitive reactance was made low enough, the generator built up its voltage exactly as had the induction machine. The exciting current was naturally very high, as the reluctance of the magnetic path was considerably greater than that of the squirrel-cage machine. It is interesting to note that the voltage wave of the machine with capacitive excitation was a sine wave, whereas the voltage wave of the machine running as a synchronous generator was not. No appreciable difference in the wave shape was observed when the field circuit was open or short-circuited. Furthermore, it was discovered that with capacitive excitation the voltage wave held its sinusoidal form under load.

Loss and Restoration of Residual Magnetism

Operating as a shunt generator, a short circuit or too great a load will cause the induction generator to lose its voltage, and the residual magnetism of the rotor is destroyed, preventing the machine from again building up. Any method that gives temporary excitation to the iron will restore the residual magnetism. A few methods that have been found are: (1) running the machine as a motor from an existing a-c system; (2) discharging a charged condenser through the stator windings while the machine is in operation; and (3) connecting a 6 volt storage battery across 2 terminals of the machine for a few moments while the machine is at rest. All 3 of these methods have been proved successful in restoring the residual magnetism, thus enabling the machine to build up its voltage; but the third method, that of using a storage battery, is by far the most practical when dealing with an isolated generator where power from an existing system cannot be obtained.

Loading

Having determined thus far that the induction machine under the influence of capacitive excitation will build up a voltage of sine-wave form and maintain this voltage with stability, the next consideration that naturally comes to mind is that of loading the machine. Can this machine be made to supply power to a load and at the same time have reasonable voltage regulation characteristics? The answer to this question follows.

Shunt Loading. The first load test consisted in placing a unity power factor load directly across the terminals of the machine with the capacitance connected as shown in the diagram of figure 1. Results of the preliminary test are shown in figure 2. Here it may be seen that the voltage falls off quite rapidly with increased load, thus further bearing out the resemblance of this machine to the d-c shunt generator. The voltage holds up better as the machine is operated at higher degrees of saturation, as might be expected.

Loads of different power factors were tried in this connection. It was found that lagging loads caused the voltage to fall more rapidly, whereas leading loads held up the voltage. The effect of these loads was the same as that of an equivalent unity power factor load with the shunt capacitance increased or decreased according to whether the load in question was leading or lagging.

Compounding. The fact that leading power factor loads tend to hold up the voltage leads to the possibility of compounding the machine, that is, causing all loads to be effectively leading by placing series capacitance in the line wires as a permanent feature. This was tried and found effective in varying degrees depending on the initial voltage or saturation. A

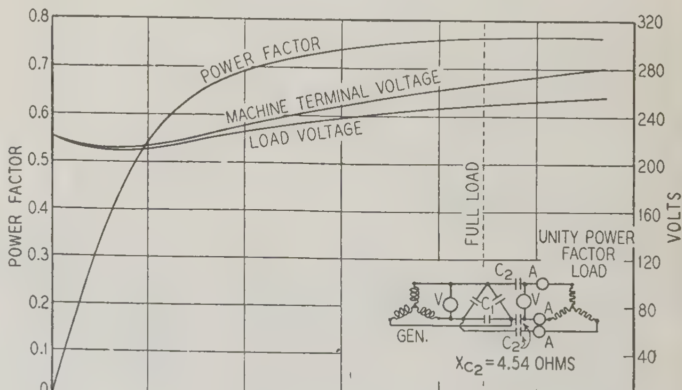


Fig. 4. External characteristics of machine of figure 1 with "flat compounding" as shown in the small diagram

family of such curves is shown in figure 3. The magnitude of the series capacitance used in this test was chosen after some experimenting, which revealed that there is some optimum value of reactance that produces the best characteristics under all degrees of saturation. A check indicated that the capacitive reactance needed corresponds quite closely to the effective inductive reactance offered by the machine windings. Further discussion of this point will be taken up later.

As to the general shape of the "compounded" curves, it may be noted that those taken at low saturation exhibit a pronounced dip initially, whereas at the higher saturations the dip practically disappears. For an explanation of this phenomenon, consider what occurs in the part of the circuit external to the machine. The external circuit then is composed of a constant capacitive reactance in series with a variable resistance (the load). When the load is light, that is, when it has high resistance, the effect of the small capacitive reactance in series with it is practically negligible. Hence, initially, all curves of the family tend to follow the straight shunt form. As the load resistance decreases, the effect of the capacitance becomes more prominent and finally governs, bringing the voltage up again. If the normal shunt characteristic will carry over this dip and hold up the voltage until the series capacitance becomes effective, there will result an approximation of "flat compounding." This reasoning is borne out by the appearance of the curves of figure 3. Figure 4 shows a typical external characteristic with load and terminal voltage plotted together with the power factor measured at the machine terminals.

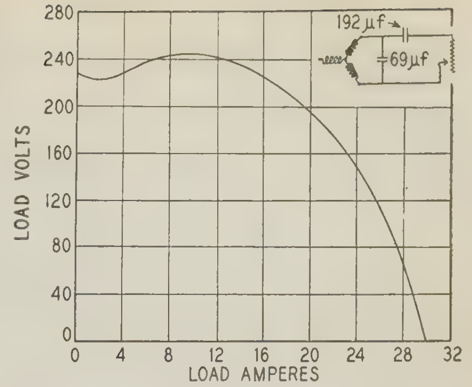
Short-Circuit Conditions

The effect of sustained overloads and sudden short circuits on any piece of electrical apparatus is of considerable importance. The investigation along this line for the induction generator with capacitive excitation was carried out in 4 sections: with both suddenly and gradually applied short circuits for the pure shunt connection and for the so-called "compound" connection.

With the shunt connection, the application of a load causes a drop in terminal voltage which also decreases the current taken by the exciting condensers. The effect is thus cumulative, and the terminal voltage drops to a point of stable equilibrium, providing that the load applied be not too great. As the load is increased further, the terminal voltage, of course, decreases more and more rapidly, receding along the saturation curve until the straight portion is reached. At this point the machine becomes unstable, and the terminal voltage and current drop rapidly to zero. This phenomenon is shown plainly by the extended curve of figure 2. Under these conditions, there is no possibility for any abnormal voltage or current; beyond an unavoidable loss of residual magnetism there are no consequences.

When the terminals of the machine with shunt connection suddenly were short-circuited, the final result was the same. There was a sudden rush of

Fig. 5. External load - voltage characteristic of machine of figure 1 compounded and connected for single phase operation as shown in diagram



current of extremely short duration through the short circuit, the magnitude of which depended upon the voltage existing at the capacitor terminals at the instant of application of the fault together with the resistance presented by the fault. This is what happens whenever a capacitance is discharged through a resistance; there are no abnormal voltages, and the current does not enter the machine. The machine current decayed in a matter of 3 or 4 cycles, depending on the time constants of the machine windings. This current never can be greater than that flowing in the windings at the time of application of the fault. All these facts were brought out by repeated oscillograms taken of current and voltage through the period of short circuit.

Short circuits applied to the compound connection present a somewhat different aspect. Series capacitance is placed in the line wires to cause the load current to lead the terminal voltage, thereby providing added excitation as the load is increased. As the load current is increased beyond a certain point, the drop in the series capacitive reactance exceeds the rise in terminal voltage afforded by the added excitation, and the load voltage falls, finally to zero, as shown by the curve of figure 5. The machine terminal voltage, however, has been rising during this progressive decrease in load resistance. The final value to which this terminal voltage will rise may be determined graphically from the saturation curve of the machine, using for a value of X_c the equivalent series value obtained from the combination of the shunt and series capacitances. This reasoning may be fitted easily to either the single or 3 phase short circuit. For the circuit shown in figure 5, the terminal voltage rose to 415 volts, this being applied to the series as well as the shunt capacitors. When this short circuit was applied suddenly, the same final results prevailed as for the gradually decreased load resistance. Short-circuiting the load merely amounts to suddenly increasing the shunt capacitance to an amount equal to the sum of the shunt and series capacitances. There may be a sudden, brief rush of current to the series capacitors at the instant of application of the fault as they become charged to, and begin to operate under, a higher voltage. However, there will be no voltage surges to damage the capacitors.

An oscillogram, selected from several taken, showing the voltage and current in the series capacitors through the period of the short circuit is

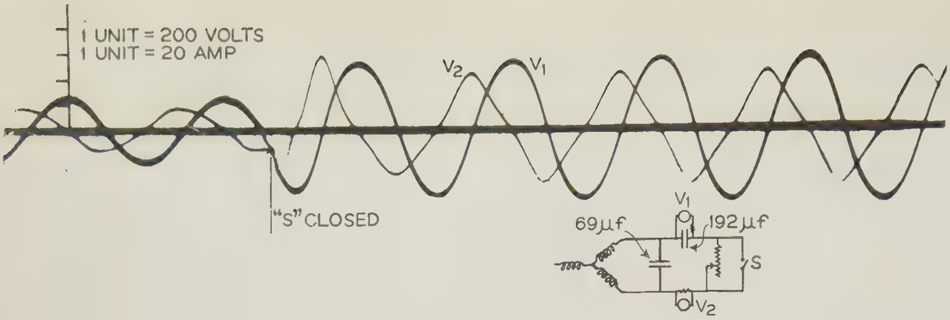


Fig. 6. Oscillogram showing voltage and current in series capacitance of compounded machine during short circuit

Conditions before switch S was closed: voltage (V_1) 175 volts; current (V_2) 12.7 amperes; load volts 238. Conditions after switch S was closed: voltage (V_1) 415 volts; current (V_2) 30.0 amperes. (All current and voltage values are effective)

reproduced in figure 6. The departure of the current from true sinusoidal form is, no doubt, a result of the abnormally high degree of saturation existing in the iron of the machine with the high terminal voltage. There is no possibility of a voltage surge, and the final steady-state voltage probably will not be in excess of twice the terminal voltage under normal conditions. Furthermore, the current will not be greater than 3 times its normal value. If series transformers are used in connection with the series capacitors, even these abnormalities are eliminated. Consequently, for the compound connection no detrimental effect on the equipment will result from a short circuit, if the series capacitors either are capable of withstanding roughly double the rated terminal voltage or are operated in connection with series transformers properly selected. The machine will be unaffected if the short circuit is removed before serious overheating occurs.

From this discussion, it may be seen that no serious effects will result from the gradual or sudden short circuit of an induction generator operating with capacitive excitation. In the shunt connection, short circuits can do no harm under any condition. In the compound connection, there need be no difficulty.

Compensation

A consideration of the familiar equivalent diagram of the induction machine, shown in figure 7, reveals that the various reactances of the machine are grouped in a T section. If these reactances remain reasonably constant, it should be possible to compensate for them completely with a suitable T or Π section of capacitance, neglecting for the moment, all voltage drops resulting from copper and iron losses. This assumption seemed reasonable from the fact that the best compounding results were obtained with a series capacitance corresponding in reactance to the appropriate value of inductive reactance to be placed on such a diagram. This general scheme was tried, but was found not to give sufficient advantage over the former method to warrant the added capacitance required.

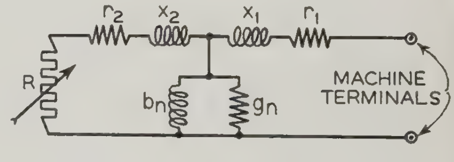
It might be supposed that with proper compounding an induction generator could be compensated to carry loads of all power factors, but such is not the case. The behavior of the voltage under different load conditions always follows the same trend as was exhibited by the shunt machine. In justification of this (assuming the validity of the equivalent circuit) it should be remembered that the resistance shown at the left of the diagram in figure 7 multiplied by I_2^2 represents the internal load of the machine. The magnitude of this resistance is given as $R = r_2\ (1-s)/s$, where r_2 is the rotor resistance referred to the stator, and s is the slip. If the slip becomes negative (machine generating) this resistance becomes negative and may be replaced by an equivalent generator, but this generator can furnish power only at unity power factor. Hence, with the machine compensated, the reactive component of the load current cannot be fed from this hypothetical generator, but must circulate through the part of the circuit that furnishes excitation. Thus, the reactive components of the load currents add or subtract from the machine excitation as before.

Capacitive Networks

Various connections of the shunt and series capacitances may be used to obtain essentially the same results as are shown in figure 3. Besides the method of placing the shunt capacitance directly across the terminals and the series capacitance in the line wires, as first tried, the idea may be reversed, placing the series capacitance inside the shunt—that is, a "long shunt" connection.

A comparison of the "long" and "short" shunt connections brings out the following facts: In the short shunt connection the voltage applied to the shunt capacitors rises with the terminal voltage; hence, more exciting current is obtained automatically in a cumulative manner. The difference between the machine and load voltages is only the drop in the series capacitors, which is small. In the long

Fig. 7. Equivalent diagram of a single phase induction machine



shunt connection the voltage applied to the shunt capacitors drops with the load voltage. Further, the load voltage in effect is tapped out of a capacitive potentiometer connection, resulting in a low ratio of load to terminal voltage, which is not to be desired. Since any other network is necessarily a compromise between the 2 simple short and long shunt connections, not much work was done in this direction. The short shunt connection was found to give results equal to any of the others, and, being

the most economical of capacitors, it was adopted as a standard.

Single or 3 Phase Operation?

Early investigations were conducted with the machine operating as a 3 phase generator with delta connected capacitors. To simplify the work an attempt was made later to operate the machine as a single phase generator. Experimentation and comparison showed that the characteristics for either are identical. This fact is brought out clearly by the curves of figure 2 where both the 3 phase and single phase curves correspond exactly as to shape. Furthermore, the bottom curve of figure 2 is for both 3 phase and single phase operation. It was discovered further that the constants or values of capacitance for either case could be translated quite easily to the other. In the single phase method, the wye connected machine was operated with 2 of the phases in series. As a result, in compensating, the series capacitive reactance must be approximately twice the 3 phase value, since it must balance out the inductive reactance of 2 of the phases. In regard to the shunt capacitance, remembering that to operate at the same voltage (either single or 3 phase) the iron of the machine must be at the same saturation, it might be supposed that the same kilovolt-ampere value of capacitance would be required for either single or 3 phase operation. This relation checked quite closely experimentally.

To obtain large values of capacitance for series use, series transformers may be used with small-capacitance high-voltage capacitors. The operation of a capacitor through a transformer gives the capacitor an effective reactance equal to its actual reactance multiplied by the square of the transformation ratio. Operation in this manner is satisfactory so long as the transformers are operated well below the knee of their saturation curves.

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Effects of Saturation on Machine Reactances

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The effects of magnetic saturation on the various types of reactances used in calculations on synchronous machines are considered in this paper. Saturation factors for the important constants used in transient and unbalanced load calculations are presented in curve form. These data are taken from short-circuit tests on a large number of machines. The saturation factor for transient reactance under conditions encountered in stability calculations is difficult to test directly so the test data are supplemented by theoretical calculations.

THE new methods of analyzing synchronous machine performance under transient or unbalanced load conditions have introduced a large number of new constants.[5,8] The method of symmetrical components requires negative and zero sequence reactances (x_2 and x_0) and an accurate analysis of transients requires transient and subtransient reactances (x_d' and x_d'') and transient and subtransient time constants (T_d' and T_d'') as well as the synchronous reactance (x_d).

These new theories were developed either on the assumption of no saturation or of fixed permeability. In 1929, the company with which the writer is associated started a series of tests to determine the effects of saturation and to check methods of calculation. Several parts of these data were presented in an A.I.E.E. paper,[6] by S. H. Wright, in 1931.

An A.I.E.E. committee report[3] on "Proposed Definitions of Terms Used in Power System Studies," by H. K. Sels, lists the constants which are effected by saturation but gives no quantitative data on saturation nor does it state which value of the constant is to be understood when the degree of saturation is not specified. It may not be desirable in a list of formal definitions to limit the value of the constant to any particular degree of saturation. However, for practical purpose it would be very useful to have standard curves showing the effects of saturation on the constants of typical machines and also to have an accepted value (either saturated or

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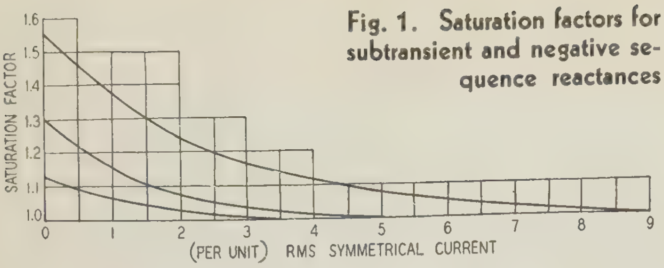


Fig. 1. Saturation factors for subtransient and negative sequence reactances

Factor is ratio of partially saturated to saturated value
Curve A—For 2 pole turbine generators with solid rotors
Curve B—For 4 pole turbine generators with solid rotors
Curve C—For salient pole machines without damper windings
For salient pole machines with damper windings no correction is necessary

unsaturated) for each constant which is to be understood when the degree of saturation is not specified. In this paper curves showing the effects of saturation on the more important constants are given. These curves are based upon the test data, except in the case of transient reactance where the test data are supplemented by calculations, since tests under conditions encountered in transient stability studies are difficult to obtain.

It is concluded that one value of each constant is all that is needed for most cases. A choice of saturated or unsaturated values for each constant as the value to be understood unless otherwise qualified is recommended in this paper. This choice is based upon the most common use of the quantities and the value which gives the least error for most applications.

Methods of Dealing With Saturation

It is generally agreed that the reactances of turbine generators are affected by saturation, and the test data of table I show that the transient reactance of salient pole machines is also affected. In using these constants for different applications it is necessary to apply correction factors if very accurate results are to be obtained. There has been considerable discussion as to which value (saturated or unsaturated) should be used as a reference.

Theoretically it would be more simple to define all the constants as unsaturated values and then apply reduction factors to obtain the saturated or partially saturated values. This method has the practical objection that if the unsaturated value of subtransient and negative sequence reactance of turbine generators were used in the calculation of short circuits, the currents obtained might be too low by as much as 35 per cent. The most common use of these 2 constants is in the calculation of short-circuit currents and those who make such calculations often do not have time, or are not sufficiently familiar with the refinements, to apply saturation factors. If the saturated values (that is, values which would be obtained by sudden short circuit from full voltage) are used, the results are correct for sudden short circuits near the machine and the errors are small for short circuits through considerable external reactance, since the machine reactance is then only a part of the total. Furthermore, if standard saturation factors are applied to these constants for turbine generators, the errors due to variations in individual machines will be greater if the saturation factors are applied to the unsaturated values, than if the saturated value is used as a base.

With these practical considerations in mind, it is suggested that the *one value which can be used in most calculations and which should be understood, unless otherwise specified, be the saturated value* for the following constants: (1) the transient reactance x_d'; (2) the direct axis subtransient reactance x_d''; (3) the quadrature axis subtransient reactance x_q''; (4) the negative phase sequence reactance x_2; (5) the zero phase sequence reactance x_0; (6) the transient time constant T_d'; (7) the subtransient time constant T_d''; and (8) the armature time constant T_a.

In using the synchronous reactance, saturation must ordinarily be considered but saturation may be dealt with by using the saturation curves of the machine; hence, it is best to define the synchronous reactance x_d as the unsaturated value. The other quadrature axis reactances and time constants of turbine generators and the quadrature axis synchronous reactance of all machines are affected by saturation. Since these constants are less commonly used and sufficient test data have not yet been obtained to determine these saturation factors definitely, it seems best to suggest that, unless otherwise qualified, the unsaturated values of these constants are to be understood.

There has been some objection to using the saturated values as a reference on the grounds that short-circuit tests at full voltage are required. However, short-circuit tests of some type[3,6] must be employed to obtain the time constants of all machines, and the transient reactance of all, except salient pole machines without damper windings. If standard saturation factors similar to those given here were adopted, the unsaturated values could be tested for by locked tests and short circuits at reduced voltage, and the correction factors applied.

Tests show that certain of the constants are not

Table I—Results of Sudden Short-Circuit Tests at Several Voltages for Salient Pole Machines

Rated Kva	Speed	Per Unit Voltage	Per Unit Transient React. x_d'	Transient Constant Time T_d'	Ratio of Value of x_d' at 100% and 50% E	Ratio of T_d' at 100% and 50% E
31,250	300	0.50	0.277			
		1.00	0.244		0.88	
30,000	720	0.48	0.40	3.45		
		0.99	0.37	2.74	0.92	0.79
1,500	900	0.50	0.40			
		1.00	0.34		0.85	0.85
7,500	360	0.51	0.565	1.9		
		0.75	0.54	1.79		
		1.04	0.54	1.70	0.95	0.89
5,000	900	0.51	0.251	1.28		
		0.514	0.261	1.35		
		1.00	0.22	0.89	0.85	0.68
		0.995	0.23	1.07	0.90	0.77
730	1,200	0.50	0.332	0.765		
		0.74	0.321	0.713		
		1.01	0.295	0.573	0.89	0.75
330	1,200	0.50	0.28			
		1.00	0.22		0.79	

appreciably affected by saturation and for these locked tests or other tests giving the unsaturated values are at all times applicable. The tests made show the following reactances to be effected to such a slight extent that for practical purposes saturation may be neglected: the subtransient and negative phase sequence reactances (x_d'', x_q'' and x_2) of salient pole machines with damper windings, the subtransient time constant T_d and zero sequence reactance x_0 of all machines. Test on one large 25 cycle single phase machine showed a reduction of subtransient reactance of 0.83 so that this type of machine should be considered an exception to the above rule. It is suggested that the same ratio of saturated to unsaturated value of x_d'', x_q'', and x_2 of large 25 cycle machines be taken as the same as that for transient reactance as shown by curve B, figure 2.

Saturation Factors

Subtransient and Negative Sequence Reactance. The average variation in the subtransient reactance of solid rotor turbine generators is plotted in curves A and B, figure 1. These data with the exception of one additional test are taken from the data given in figure 23 of S. H. Wright's paper.[6] The term solid rotor includes plate rotors but not those made of thin laminations. The test data for values of current less than 1.5 times rated current were determined by locked tests and those above this value were determined by sudden short-circuit currents.

For these same machines where line to line short circuits were also made the negative phase sequence reactance was determined from the single phase subtransient $x_1''\phi$ as:

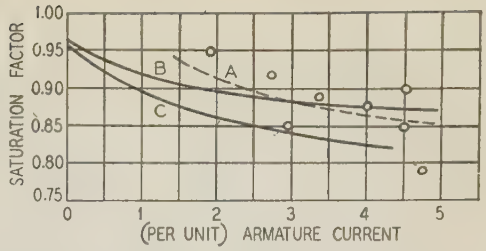
$$x_2 = \sqrt{3}(x''_1\phi) - x_d''$$

These results, although less consistent than the values of x_d'' showed that the same saturation factors

Table II—Results of Sudden Short-Circuit Tests at Several Voltages for Turbine Generators

Rated Kva	Speed	Per Unit Voltage	Per Unit Transient React. x_d'	Transient Time Constant T_d'	Subtransient Time Constant T_d''	Ratio of Value of x_d'' at 100% and 50% E	Ratio of T_d at 100% and 50 % E
75,000	1,800	0.335	0.268	1.57	0.037		
		0.667	0.27	1.53	0.029		
		1.00	0.238	1.53	0.035	0.89	0.97
43,750	1,800	0.50	0.27	1.15	0.016		
		0.75	0.245	1.11	0.020		
		1.00	0.245	1.00	0.020	0.91	0.87
18,750	3,600	0.50	0.161	0.65			
		0.767	0.152	0.593			
		1.00	0.140	0.59		0.87	0.87
		0.53	0.162				
		0.78	0.147				
		1.00	0.14			0.87	
12,500	3,600	0.50	0.155	0.55	0.097		
		1.00	0.135	0.54	0.047	0.87	0.98
9,375	3,600	0.51	0.155	0.555	0.040		
		0.515	0.150	0.55	0.030		
		1.05	0.135	0.44	0.037	0.87	0.825
8,575	3,600	0.47	0.133	0.455	0.038		
		0.75	0.117	0.438	0.036		
		1.00	0.120	0.433	0.052	0.90	0.95

Fig. 2. Saturation factors for transient reactance of salient pole machines



Curve A—Short circuit test from rated voltage, no load
Curve B—Normal operation as a motor or generator
Curve C—Condenser under load
Circles—Test points from short circuits at no load

(curves A and B, figure 1) determined for the subtransient reactance could be used. A complete analytical calculation of transients in turbine generators is impossible since the number of damping circuits formed by the solid iron of the rotor is infinite. An approximate analysis does indicate, however, that for the same root mean square symmetrical current, the depth of penetration in the iron of the flux on 60 cycle locked test is about the same as that on short circuit at the end of the first half cycle. Since the peak at about one-half cycle is the first point on the oscillogram which influences the determinations of x_d'', it would seem that the locked test should give about the same reactance as sudden short circuit for the same currents. The test curves (figure 23 of S. H. Wright's paper[6]) do not show any locked and sudden short-circuit values at the same current, but the points from both tests seem to be on the same general curve. In several tests load was dropped suddenly and the initial rise in voltage measured to give the subtransient reactance at lower currents. These values agree quite well with the values obtained by locked test at the same current.

The subtransient and negative sequence reactances of salient pole machines as determined by locked tests, sudden short circuit, or other tests[6] agree quite well and show a negligible amount of saturation. Theoretically, one would expect an appreciable saturation in the tips of the partially closed damper slots, but this generally constitutes only about 0.10 or 0.15 of the total, hence, the reduction in the total reactance is negligible.

Saturation Factors for Transient Reactance. The transient reactance for a number of turbine generators and salient pole machines was determined by short circuits at full voltage and at one or more lower voltages. The results of these tests are shown in tables I and II. There are a number of inconsistencies in the several values determined for some of the machines, indicating a maximum test error of about ±8 per cent. However, these tests do indicate definitely that for the machines tested the average ratio of the transient reactances determined by short circuits at full voltage and half voltage is 0.88. These test ratios for salient pole machines are shown by the points on figure 2. Curve A, figure 2, gives the calculated reduction of the transient reactance as determined for a typical salient pole machine by the method developed in appendix A and seems to agree within the limits of error with the test results.

Curve B shows the reduction factor for a typical

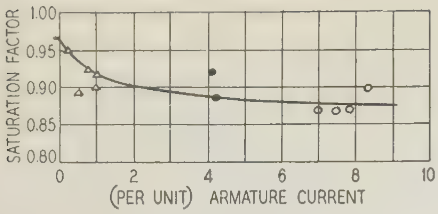


Fig. 3. Saturation factors for transient reactance of turbine generators

Circles—Test points on 2 pole turbine generators, short circuit from full voltage
Dots—Test points on 4 pole turbine generators, short circuit from full voltage
Triangles—Test values obtained by suddenly applied loads, measuring transient change in voltage

salient pole machine under conditions similar to those encountered in transient stability problems. In the calculation of curve *B*, the machine was assumed to be operating with $(E_d' + E_s) = 1.30$ and $x_d = 1.15$ (see appendix *B* for symbols) which would correspond to an initial condition of unity power factor with the saturation ampere turns equal to 0.3 of the gap ampere turns. It was also assumed that the quadrature axis current was equal to the direct axis current, although the quadrature axis current can vary quite widely without greatly affecting the result, since it adds to the saturation on one pole tip and subtracts on the other. The range of current encountered in transient stability problems is generally from 1 to 3 times rated current and the average reduction between these points, indicated by curve *B*, for these currents is 0.895.

Curve *C* is calculated by the same method for a synchronous condenser which may be swinging about the mean position. $(E_d' + E_s) = 1.45$, which corresponds to a saturation ampere turns equal to 0.25 of gap ampere turns for $x_d' = 0.20$ and $x_d = 1.40$. The range of currents encountered in calculating the swings of a condenser in a stability problem is generally from 1 to 2 for which the average reduction factor, from curve *C*, is 0.87.

For turbine generators the tested transient reactances (table II and figure 3) show similar ratios of values measured by short circuit at full and at half voltage. The effects of saturation on the transient reactance of turbine generators cannot be calculated by any relatively simple manner, such as that used for salient pole machines. The calculation of the reduction factor k_{sm} for the saturation of the main magnetic circuit is the same as for salient pole machines. This fixes the reduction in transient reactance when operating at full voltage with low currents as about 0.97. The remainder of the curve is drawn from the test points in figure 3.

Saturation Factors for Time Constants. Tests[6] show that the open circuit transient time constant T_{d0}' is not appreciably affected, nor is the subtransient time constant T_d'' of either turbine generators or salient pole machines.

The test data of tables I and II show that on the average the transient time constant T_d' varies in the same manner as the transient reactance. If the variation is assumed to be exactly the same, the relation $T_d' = \dfrac{x_d'}{x_d} T_{d0}'$ is still maintained.

Summary

From the data presented here, it is concluded that there is one value of each of the important constants of a synchronous machine which can be used for most purposes and which should be understood unless the value is otherwise qualified. The one value to be used for most purposes is the saturated value for the following constants:

Transient reactance	$= x_d'$
Direct subtransient reactance	$= x_d''$
Negative sequence reactance	$= x_2$
Zero sequence reactance	$= x_0$
Quadrature axis subtransient reactance	$= x_q''$
Transient time constant	$= T_d'$

The synchronous reactance x_d should be understood to be the unsaturated value as now defined by the A.I.E.E. Data have been presented in the curves of figures 1, 2, and 3 from which the relations between saturated, unsaturated, or partially saturated values can be obtained.

Table III gives the average ratios between the saturated and the unsaturated values of the constants.

The term "saturated value" as used here means the value which would be determined by a sudden short circuit from full voltage. This does not mean that it would be necessary to make sudden short-circuit tests at full voltage in every case to establish the value of the constants, since some of the simpler

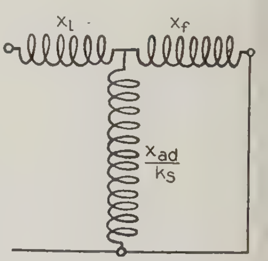


Fig. 4. Equivalent circuit for transient reactance

tests can be made for the unsaturated values and the saturation factors given here applied to determine the saturated value.

The curves of figures 1, 2, and 3 may be used to determine the saturation factors to be applied to either saturated or unsaturated values of normal machines. Although individual machines will vary somewhat from these average factors based upon typical machines, the application of such factors does give an increase in the accuracy over that which could be obtained by using a single value.

Appendix A—Effect of Saturation of the Main Magnetic Circuit

The total reduction of transient reactance due to saturation may be considered in 2 parts, first, due to saturation of the main magnetic circuit, and second, due to saturation of the leakage paths. These will be calculated separately as 2 separate factors which may be multiplied to give the total reduction factor. This method is not rigorously correct, since saturation in the one part affects the other but these secondary effects are small and will be neglected.

The reduction factor k_{sm} due to the saturation of the main magnetic circuit is very readily calculated if the transient reactance is

resolved into its components: armature leakage x_l, field leakage x_F, and magnetizing reactance x_{ad} as shown in the equivalent circuit of figure 4.

The reduction in permeability of the parts of the main magnetic circuit has an effect equivalent to increasing the air gap or of directly reducing x_{ad}. If the total ampere turns required to take care of saturation is $F_i = E_s F_g$ where F_g = the no-load gap ampere turns, and E_s = per unit excitation required for saturation; the gap ampere turns for the given flux is $E_g F_g$, where E_g = per unit air gap voltage. Then the factor by which x_{ad} is divided is: $k_s = \dfrac{E_g + E_s}{E_g}$.

The unsaturated transient reactance x_{du} may be calculated as

$$x_{du}' = x_l + \frac{x_F \cdot x_{ad}}{x_F + x_{ad}} \qquad (1)$$

The saturated value x_d' may be calculated as:

$$x_d' = k_{sm} x_{du} = x_l + \frac{x_F \cdot x_{ad}}{k_s x_F + x_{ad}} \qquad (2)$$

From this relation k_{sm} may be calculated as:

$$k_{sm} = \left[\frac{x_l}{x_{du}} + \frac{x_F}{x_{du}}\left(\frac{x_{ad}}{k_s x_F + x_{ad}}\right)\right] \qquad (3)$$

For a normal relation between the reactances: $k_{sm} = 0.98$ for $k_s = 1.15$, which is typical of no load; and for $k_s = 1.30$, which is a typical full load value, $k_{sm} = 0.957$.

Appendix B—Effect of Saturation of the Pole Tips on Transient Reactance of Salient Pole Machines

The effects of pole tip saturation were studied originally by calculating the densities throughout the pole tip for various values of armature and field currents. Out of this study the following simplified method was developed based upon the assumption that the ampere turn drop in the pole tip is the same as if the density at every point was the same as at a point A, $^1/_3$ the way from the body to the end of the pole tip.

The pole tip leakage flux per inch of length $\phi_{pt} = \lambda_{pt} F$ where F is the total field ampere turns per pole and λ_{pt} is 3.19 times the ratio of effective width to length of path for the pole tip flux up to the point C. See figure 5. The point C was chosen so the pole tip flux up to this point includes the differential leakage of the field which was caused by harmonics of the field form. The differential leakage is assumed to vary with saturation in the same manner as the pole tip leakage.

The air gap flux per inch ϕ_{gt} which enters the pole tip up to the point A (which is $^1/_3$ the way from the pole body out to the end of the pole tip; see figure 5) may be calculated by assuming that the net magnetomotive force acting across the gap at the center of this section (point B, figure 5) is the field ampere turns F minus the armature magnetomotive force at this point. The point B is normally about 60 degrees from the pole center and the ampere turns acting across the gap may be taken as $F_A\left(\dfrac{I_d}{2} \pm 0.866 I_q\right)$ where F_A = the maximum armature magnetomotive force. The assumption that the ampere turn drop is the same as if the density were the same as at point A throughout the pole tip, leads to a simple method of

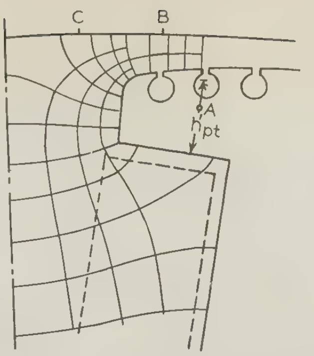


Fig. 5. Diagram of pole tip flux at no load, no saturation

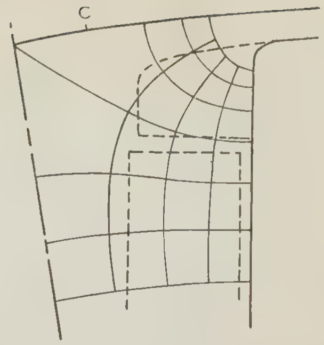


Fig. 6. Diagram of pole tip flux at no load assuming unit permeability in the pole tip

calculating the saturation effects. The saturation curve of the iron will be approximated by assuming that for densities below 125,000, negligible saturation exists and any flux above this value requires the same ampere turns as if it were in air. The pole tip leakage field assuming unit permeability for the pole tip is shown in figure 6; the pole tip and belt leakage for this condition is about 0.2, the value which would be obtained with no saturation; and I_d and I_q are the per unit direct and quadrature axis components of current. The + sign is used for one pole tip and − for the other. It can be shown that, approximately:

$$\phi_{gt} = \lambda_{gt}\left[F - F_A\left(\frac{I_d}{2} \pm 0.866 I_q\right)\right]$$

The density B_{Pt} which would exist at the point A if no saturation existed would be:

$$B_{pt} = \frac{\phi_{pt} + \phi_{gt}}{h_{pt}'} = F\frac{(\lambda_{gt} + \lambda_{pt})}{h_{pt}'} - F_A\left[\frac{I_d}{2} \pm 0.866 I_q\right]\frac{\lambda_{gt}}{h_{pt}'},$$

where h_{pt}' = depth of pole tip at point A, as shown by figure 5; subtract $^1/_2$ the depth of the damper bar to give effective depth.

As a reference it is convenient to calculate the pole tip density at no load (B_0)

$$B_0 = F_g\left(\frac{\lambda_{pt} + \lambda_{gt}}{h_{pt}^1}\right)$$

where F_g = the gap ampere turns at rated voltage.

$$\left[B_{pt} = B_0\left\{\frac{F}{F_g} - \left(\frac{\lambda_{gt}}{\lambda_{gt} + \lambda_{pt}}\right)\frac{F_A}{F_g}\left[\frac{I_d}{2} \pm 0.866 I_q\right]\right.\right]$$

Hence, this part of the reactance is reduced by the factor:

$$\left[\frac{125{,}000}{B_{pt}} + 0.2\left(1 - \frac{125{,}000}{B_{pt}}\right)\right]$$

For the purpose of obtaining a simple result applying to normal machines, certain typical relations will be assumed:

$$\frac{\lambda_{gt}}{\lambda_{gt} + \lambda_{pt}} = 0.65; \quad \frac{F_A}{F_g} = 0.845 X_{ad} I_d$$

then:

$$\frac{F}{F_g} = [E_d' + E_s + I_d(X_d - X_d')]$$

and assuming:

$$X_{ad} = 0.9 X_d \text{ and } X_d - X_d' = 0.78 X_{ad}$$

then

$$B_{pt} = B_0[E_d' + E_s + 0.375 X_d(I_d \pm 2I_q)]$$

The value of B_0 varies quite a little so that some variation in saturation may be expected, but a typical value of B_0 = 83,000 will be used. It will also be assumed that $^1/_3$ of the total reactance is effected by pole tip saturation:

$$k_{sl} = 0.735 + \frac{0.40}{E_d' + E_s + 0.375 X_d(I_d \pm 2I_q)} \qquad (4)$$

Table III—Average Ratios Between Saturated and Unsaturated Values of Constants

Constant	Salient Pole Machine: With dampers	Salient Pole Machine: Without dampers	Turbine Generators (Solid rotor): 2 pole	Turbine Generators (Solid rotor): 4 pole
Transient reactance	0.88	0.88	0.88	0.88
Subtransient reactance	1.0	0.88	0.65*	0.77*
Negative sequence reactance	1.0	0.88	0.65*	0.77*
Zero sequence reactance	1.0	1.0	1.0	1.0
Transient time constant	0.88	0.88	0.88	0.88

* The ratio of the saturated value to the rated current value of subtransient and negative sequence reactance of 2 pole turbine generators is 0.73, and the same ratio for 4 pole turbine generators is 0.87.

For large 25 cycle single phase machines the ratio of saturated to unsaturated value of subtransient and negative sequence reactances is 0.88.

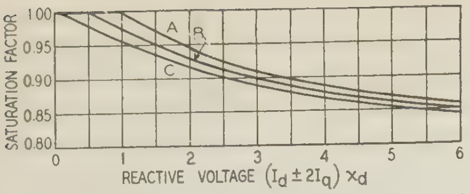


Fig. 7. Reduction factor k_{sl} as a function of $(I_d \pm 2I_q)x_d$

Curve A—$(E_d' + E_s) = 1.15$; typical of short circuit from no load

Curve B—$(E_d' + E_s) = 1.30$; typical of machine at 1.0 to 0.8 power factor

Curve C—$(E_d' + E_s) = 1.45$; typical condenser

From equation 4 the curves of figure 7 are calculated. They give k_{sl} as a function of $(I_d \pm 2I_q)$ for different values of $(E_d' + E_s)$. The factor is to be calculated using both signs for I_q and the 2 results averaged. The net factor k_{sl} times k_{sm} gives the total reduction factor for transient reactance of salient pole machines.

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Complex Hyperbolic Function Charts

Complex hyperbolic function charts covering the range ordinarily found in problems dealing with long electric power transmission lines are presented herewith. By restricting the charts to this range, it has been possible to draw them to a large scale so that good accuracy can be obtained from these comparatively small charts.

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Cambridge

THE important pioneer work of Dr. A. E. Kennelly in developing the use of complex hyperbolic functions for the solution of alternating current problems is well known. His tables and charts of complex hyperbolic functions have been of great service, but they cover a range so broad that the power transmission engineer finds difficulty in obtaining from them precise values. The purpose of the small set of charts presented herewith is to make possible more rapid, accurate, and convenient solutions of problems dealing with long electric power transmission lines. Only the portion of the complex plane lying in the range of power transmission problems has been mapped. This makes possible the use of a large scale. The range covered is from 0 to 290 miles at 60 cycles per second, and from 0 to 700 miles at 25 cycles.

The independent variable used in mapping is ZY, or θ^2, rather than θ. This obviates the necessity of taking the square root of ZY to find θ, which has been the common practice. It has the further advantage of causing adjacent curves of constant size of the independent variable to be nearly equidistant, which is a considerable advantage in legible mapping and accurate reading.

By careful use of the charts, with visual interpolation, a precision of 1 part in 10,000 may be obtained. If only slide rule accuracy is desired, it may be obtained by reading only to the nearest divisions of the function scales.

It has been customary to use the following formulas for solving steady-state long-line problems:

$$E_G = E_L \cosh\theta + I_L Z_0 \sinh\theta \qquad \text{vector volts} \qquad (1)$$

$$I_G = I_L \cosh\theta + \frac{E_L}{Z_0}\sinh\theta \qquad \text{vector amperes} \qquad (2)$$

or

$$E_L = E_G \cosh\theta - I_G Z_0 \sinh\theta \qquad \text{vector volts} \qquad (3)$$

$$I_L = I_G \cosh\theta - \frac{E_G}{Z_0}\sinh\theta \qquad \text{vector amperes} \qquad (4)$$

in which $\theta = \sqrt{ZY}$, $Z_0 = \sqrt{Z/Y}$, and Z and Y are respectively the total series impedance and the total shunt admittance per phase; E_G, E_L, I_G, and I_L are the voltages and currents at the generator and load ends, respectively, of the line.

The following formulas are equivalent to formulas 1, 2, 3, and 4 and less laborious to use:

$$E_G = E_L \cosh\theta + I_L Z \frac{\sinh\theta}{\theta} \qquad \text{vector volts} \qquad (5)$$

$$I_G = I_L \cosh\theta + E_L Y \frac{\sinh\theta}{\theta} \qquad \text{vector amperes} \qquad (6)$$

A paper recommended for publication by the A.I.E.E. committee on power transmission and distribution. Manuscript submitted July 30, 1934; released for publication Oct. 2, 1934.

or

$$E_L = E_G \cosh\theta - I_G Z \frac{\sinh\theta}{\theta} \quad \text{vector volts} \quad (7)$$

$$I_L = I_G \cosh\theta - E_G Y \frac{\sinh\theta}{\theta} \quad \text{vector amperes} \quad (8)$$

The necessity of calculating Z_0 is eliminated. Also, the necessity of having a chart of sinh θ is eliminated, and 3 charts are sufficient, whether the solution is to be carried out by formulas 5 to 8, or by an equivalent π or T circuit. In the equivalent π, the architrave or top impedance Z' and the pillars or upright admittances $Y'/2$ have values equal respectively to:

$$Z' = Z\frac{\sinh\theta}{\theta} \text{ and } \frac{Y'}{2} = \frac{Y}{2}\frac{\tanh\theta/2}{\theta/2}$$

In the equivalent T line the arm impedances $Z''/2$ and the upright admittance Y'' are:

$$\frac{Z''}{2} = \frac{Z}{2}\frac{\tanh\theta/2}{\theta/2} \text{ and } Y'' = Y\frac{\sinh\theta}{\theta}$$

The original drawings for the charts were made to a large scale on heavy art board and have been reduced photographically to approximately 1/4 size. The points for drawing the lines on the charts were located graphically by adding vectors representing the individual terms in the series expansion for each function, as given in a succeeding paragraph. Several hundred points on each chart also were checked against values given in Kennelly's tables or computed independently. In all cases the accuracy was within 1/100 of 1 per cent.

The series expansions of the 3 functions follow:

$$\cosh\theta = 1 + \frac{ZY}{2} + \frac{(ZY)^2}{24} + \frac{(ZY)^3}{720} + \ldots$$

$$\frac{\sinh\theta}{\theta} = 1 + \frac{ZY}{6} + \frac{(ZY)^2}{120} + \frac{(ZY)^3}{5040} + \ldots$$

$$\frac{\tanh\theta/2}{\theta/2} = 1 - \frac{ZY}{12} + \frac{(ZY)^2}{120} - \frac{17(ZY)^3}{20{,}160} + \ldots$$

One advantage of using the 3 functions chosen is that each of them remains nearly equal to unity for small values of its argument. Consequently, the range that must be covered in the variation of the function is reduced to such an extent that great precision is easily possible in the charts.

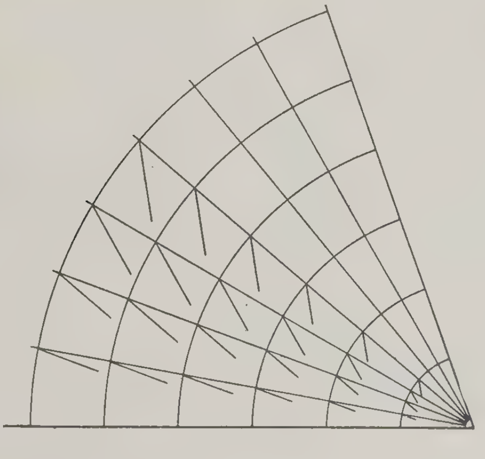


Fig. 1. A partially constructed chart

The first term of the series is the horizontal unit vector. Second term vectors have been drawn, and some of the third term angle lines

In drawing the charts, the origin of co-ordinates was allowed to fall far to the left of the drawing paper. The horizontal unit vector was shown only near its terminal point. From the terminal point, angle lines were drawn for each degree of ZY, and arcs of circles were struck about this point for each hundredth in the argument size. The points of intersection of these arcs and angle lines represent the sum of the first 2 terms of the series. The third term is representable by a vector drawn at an angle double that of the second term and was added by drawing a series of lines from the intersection points at the appropriate angles. A drafting machine was used and after setting it at the correct angle, all third-term angle lines having that angle could be drawn rapidly. Figure 1 shows this stage of construction. After the entire set of angle lines had been drawn, a pair of dividers was set for the length of the third term corresponding to a definite size of the argument, and this length was laid off along all angle lines corresponding to that size. This construction is indicated in figure 2. Fourth and succeeding terms were added in a similar manner.

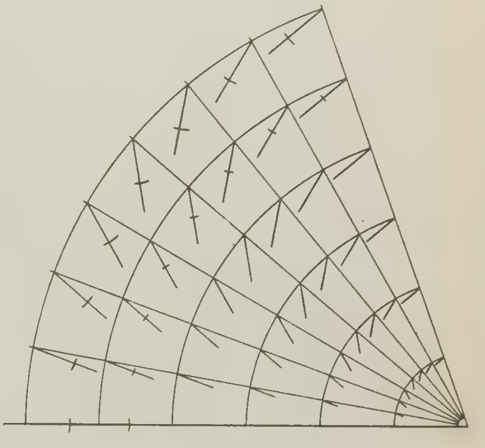


Fig. 2. Chart of figure 1 in a further stage of completion

All the third term angle lines have been drawn, and 2 sets of third term sizes have been laid off with compass

The basic co-ordinate scales necessarily had to be in polar form, since the size and angle were the basic co-ordinates and graphic construction used. The range is such, however, that the curvature and convergence of the lines are hardly noticeable. Precise geometric methods were used to lay out the main points, and large railroad curves were used in the inking of the final lines.

Example of Use

A transmission line has total series impedance per phase, Z, of 200.0 $\underline{/80.00°}$ vector ohms, and total shunt admittance, Y, of 0.00130 $\underline{/90.00°}$ vector mho per phase to neutral. Find cosh θ and $\frac{\sinh\theta}{\theta}$.

$$ZY = 200.0\ \underline{/80.00°} \times 0.00130\ \underline{/90.00°} = 0.260\ \underline{/170.00°}$$

Entering chart I with this value of ZY, it is found that cosh θ = 0.8750 $\underline{/1.41°}$. Similarly, from chart II, $\frac{\sinh\theta}{\theta}$ = 0.9578 $\underline{/0.44°}$.

Chart I. Hyperbolic Cosine of θ

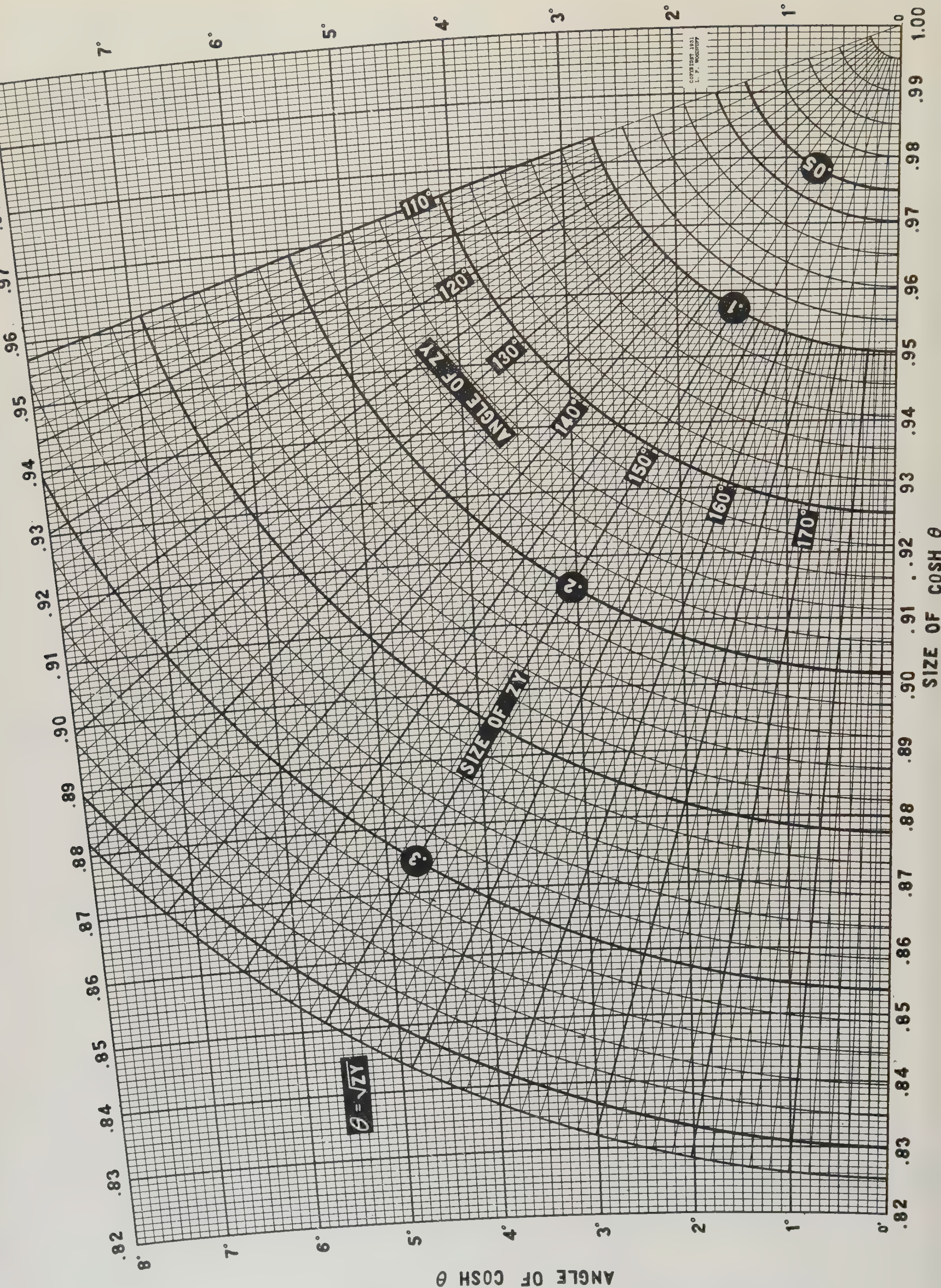
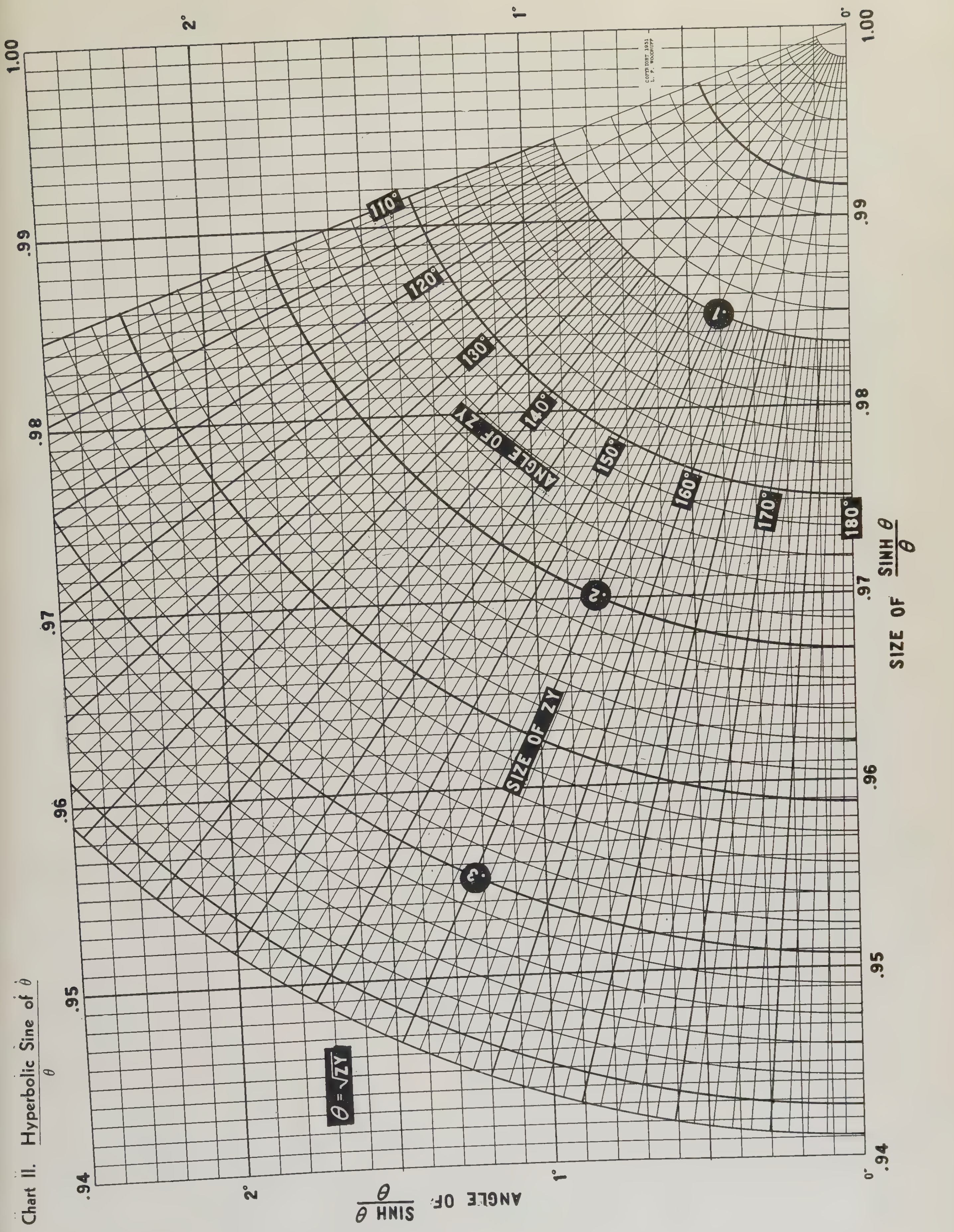


Chart II. Hyperbolic Sine of $\frac{\theta}{\theta}$



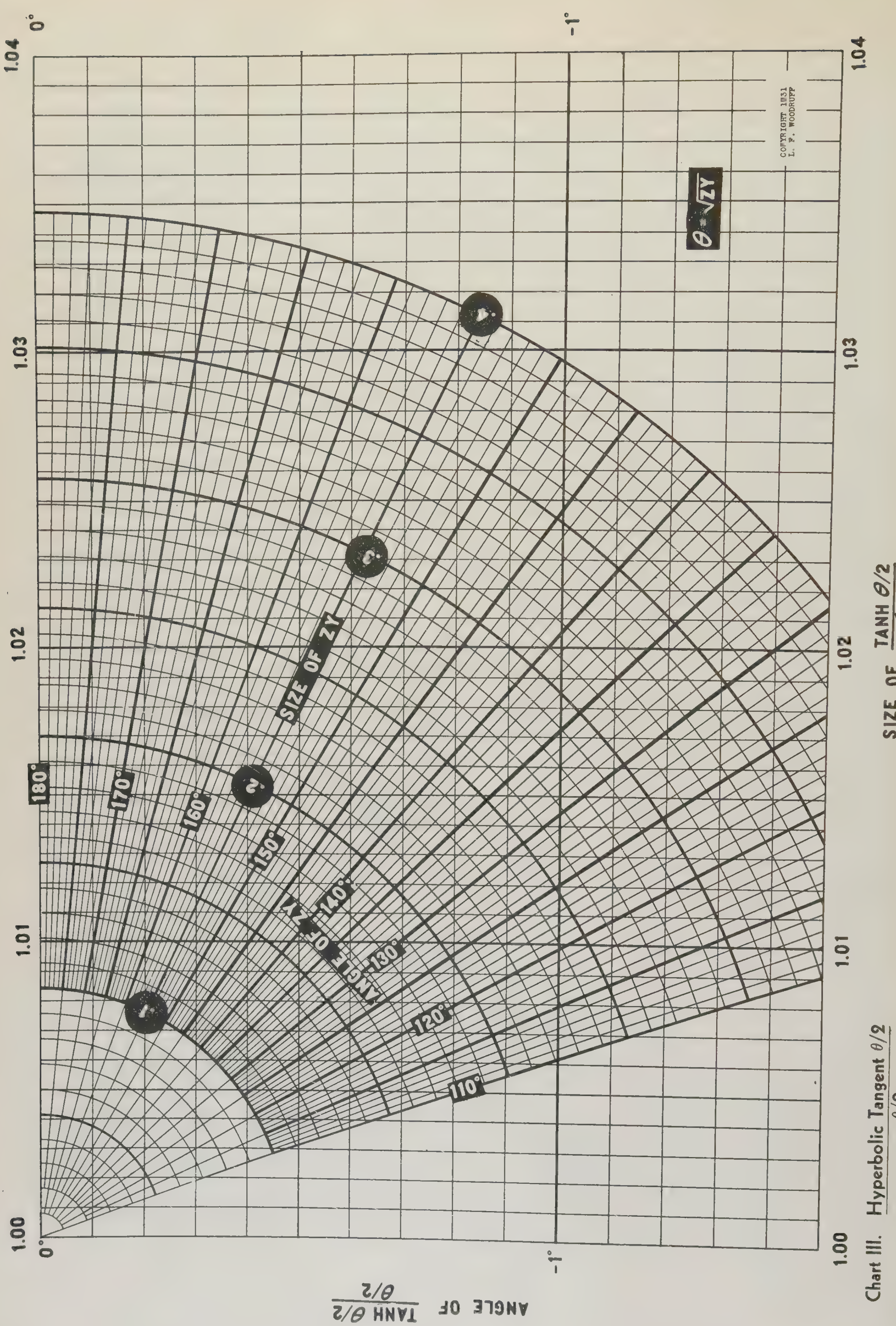


Chart III. Hyperbolic Tangent $\frac{\theta/2}{\theta/2}$

Discussions

Of A.I.E.E. Papers—as Recommended for Publication by Technical Committees

In order to provide additional space for the publication of summer convention papers in this issue the discussion has been limited to a total of 5 pages, in which appear the discussion of a paper presented at the 1934 A.I.E.E. North Eastern District meeting, Worcester, Mass., May 16–18, and several discussions and one authors' closure of papers presented at the 1935 A.I.E.E. winter convention, New York, N. Y., January 22–25, 1935. Other discussions of winter convention papers appear in Electrical Engineering for March 1935, pages 322–35, and April 1935, pages 431–9; further discussions and authors' closures will be published in later issues.

Heat Flow in Turbine Generator Rotors

Discussion of a paper by C. E. Peck published in the October 1934 issue, pages 1359–65, and presented for oral discussion at the electrical machinery session of the winter convention, New York, N. Y., January 22, 1935.

D. S. Snell (General Electric Co., Schenectady, N. Y.): In the past few years several attempts have been made, chiefly by French and German investigators, to obtain a rational solution to the problem of heat flow in a turbine generator rotor. For the most part, however, the solutions obtained have been somewhat too involved to be of practical value to the designer and also have been based upon certain simplifying assumptions which, for many types of rotor construction, are not justifiable. This paper, I believe, represents a distinct advance over the work that has been previously done in this field in that the solution neglects no important factors, and also is not too involved for use in practical design calculations. The purpose of this discussion is to suggest a method for obtaining the overall temperature rise constant of the rotor body, using the equations developed in the paper, which takes account of the difference in the cooling conditions at different parts of the body.

With the type of rotor ventilation considered in the paper the internal cooling conditions vary considerably throughout the rotor, so that the use of an average surface heat transfer coefficient for the internal ducts and an average temperature rise for the internal cooling air in calculating the temperature rise constant of the body may not always lead to accurate results. I would consider it more accurate, in calculating this constant, to assume the different sections of the rotor which have dissimilar cooling conditions as thermally insulated from each other, and to calculate the temperature rise constant for each section separately. A weighted average of these constants could then be taken to represent the temperature rise constant of the body.

In figure 1 of this discussion is shown a representative section of a rotor body divided into sections for which the cooling conditions are dissimilar. There are indicated, for the rotor considered, 21 sections for which different temperature rise constants could be calculated. It can be shown however, that the cooling conditions for sections 11–15 do not differ greatly from the conditions for sections 16–21, also that the effect on the total temperature rise constant of the body of the inferior cooling conditions for sections 1–10 as compared with sections 11–21 can be allowed for through a correction factor. It should be possible, therefore, to determine a satisfactory temperature rise constant for the rotor body by calculating the temperature rise constants for sections 11–15 only and applying a correction factor to the resultant weighted mean constant.

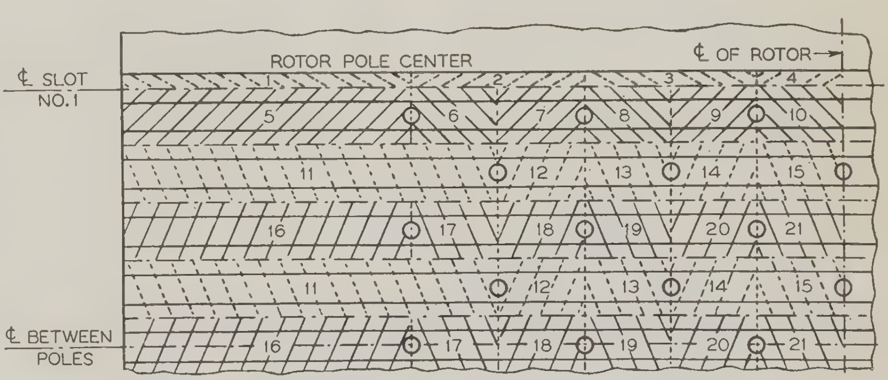


Fig. 1 (above). Development of rotor surface showing division of body into sections having dissimilar cooling conditions

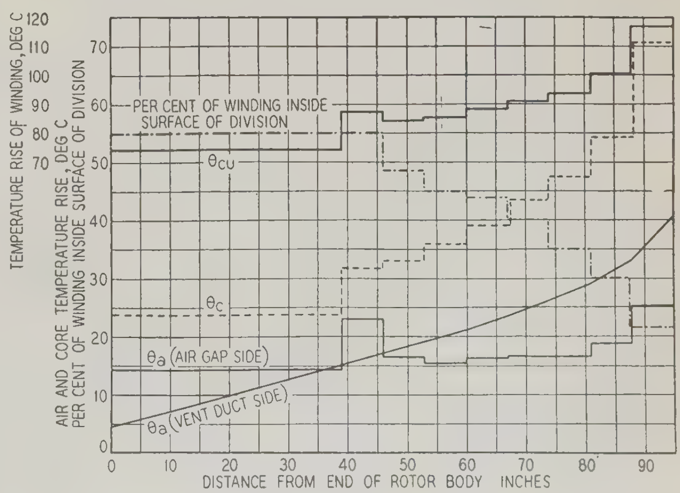


Fig. 2. Calculation of temperature rise of a turbine generator rotor winding

To take account of the elevation of the temperature of the cooling air in passing through the body, the ambient air temperature rise θ_a in the equations for the copper and iron temperature rises inside the surface of division should be taken as the rise of the air up to the rotor section under consideration, and the surface heat transfer coefficients for the axial and radial ducts should be referred to this temperature. A convenient equation for calculating the heat transfer coefficient on this basis is given by Richter in his book "Elektrische Machinen," volume I, page 324, and is as follows:

$$h = \frac{scrv}{2L}(1-e^{-m}) \text{ watts per square centimeter per degree centigrade}$$

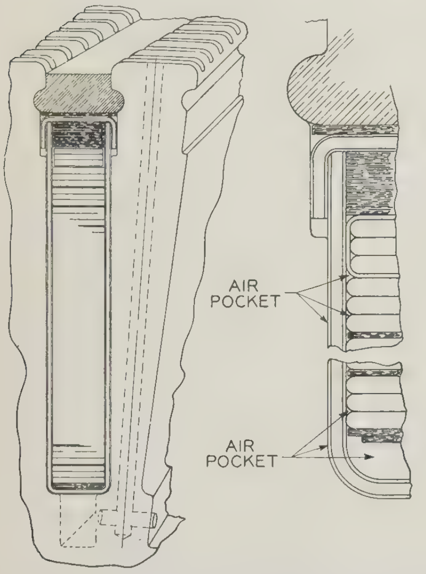
where

$$m = 0.1448\,\frac{L^{0.946}}{(2r)^{1.16}}\left(\frac{k}{scv}\right)^{0.214}$$

L and r are the duct length and hydraulic radius, respectively, in centimeters; v the air velocity in centimeters per second; k

the thermal conductivity in watts per degree centigrade per centimeter; s the specific weight in grams per cubic centimeter; and c the specific heat in joules per degree centigrade per gram for air at the temperature $\frac{t_0 + t_k}{2}$, where t_0 is the temperature of the air entering the duct and t_k the mean temperature of the duct walls.

In figure 2 is shown the temperature rise



Figs. 3 and 4. Rotor slot ideal for heat flow, and same slot with such air pockets as may form

of the body part of the field winding for a rotor 190 inches long, calculated in the above manner for the generator operating at zero power factor, overexcited. This rotor was provided with 40 axial ducts, and an average of 9.5 radial ducts per tooth, spaced 14 inches apart. The calculation shown in figure 2 is for a tooth remote from the pole center, such as number 2 or 4 in figure 1, and assumes the tooth to be divided into 9 sections thermally insulated from each other, the first section from the end of the body including the distance to the first radial duct, the other sections including $^1/_2$ the distance between adjacent ducts. From this calculation, the mean temperature rise constant of the body, referred to the average of the air temperatures in the axial ducts and air gap, was found to be 3.18 degrees centigrade per watt per inch of coil. For the ventilated end winding the calculated temperature rise constant was 4.86 degrees per watt per inch. Combining these 2 constants in accordance with equation 8 of the paper, the mean temperature rise of the winding θ_{cum} for the load considered was calculated to be 92.8 degrees centigrade. The measured temperature rise for this load was 86.5 degrees centigrade. The agreement between calculation and test is thus within 7 per cent, which, for this type of calculation can be regarded as very good, and indicates the general reliability of Peck's solution to the heat flow problem for turbine generator rotors.

S. H. Mortensen (Allis-Chalmers Mfg. Co., Milwaukee, Wis.): Progress in electrical machine design has been achieved through improvements in available construction materials combined with a better understanding of factors affecting machine operation. This paper is a valuable contribution to the latter. To those who have been active in the development of high speed turbine generators it is most interesting to see a comprehensive analytical method for predetermining rotor heating. It is an achievement to have put into a workable form a problem involving heat generation, flow, and dissipation in more than one plane in a body of irregular configuration and heat conductivities. As the agreement between the calculated rotor heating and test values depends upon the choice of constants derived from tests, a few remarks bearing upon the latter may be of interest. Types of ventilation mentioned in the following discussion pertain to machines made by the Allis-Chalmers company.

Briefly, the main constants needed for predetermining rotor temperature rise must take into consideration its heat losses and the thermal resistivity of its materials and contact surfaces, combined with the coefficient of heat transfer between its radiating surfaces and ventilating air.

Of these factors the magnitude and distribution of rotor heat losses are easy to predetermine, except in cases involving single phase or unbalanced polyphase operation. In modern machines with balanced loads, rotor stray losses are negligible and the main rotor heat loss is the I^2R of excitation.

Factors for thermal conductivity of the rotor materials can also be predetermined with accuracy. It is a more difficult problem to arrive at the proper constants for thermal resistances of the surfaces between the heated copper and the rotor iron. Inconsistencies in heating results on duplicate machines frequently can be attributed to air pockets resulting from inaccuracies in the dimensions of the rotor insulation, copper, and slots. This condition is brought out in figures 3 and 4 of this discussion, of which figure 3 depicts a rotor slot ideal for heat flow, because of the absence of air pockets. Figure 4 shows the same slot with such air pockets as may result from inaccuracies in winding, slot machining, and shrinkage of insulation materials. The effect of the air pockets upon the temperature gradients between copper and iron could be predetermined, if the magnitude of the air pockets were known.

The constant, taking into consideration the coefficient of heat transfer between the respective rotor radiating surfaces and the ventilating air, varies considerably with different types of stator and rotor ventilation and must, for that reason, be derived by experimentation. Figure 5 shows the type of ventilation used on Allis-Chalmers' larger machines. A great many schemes for increasing rotor output by improved heat

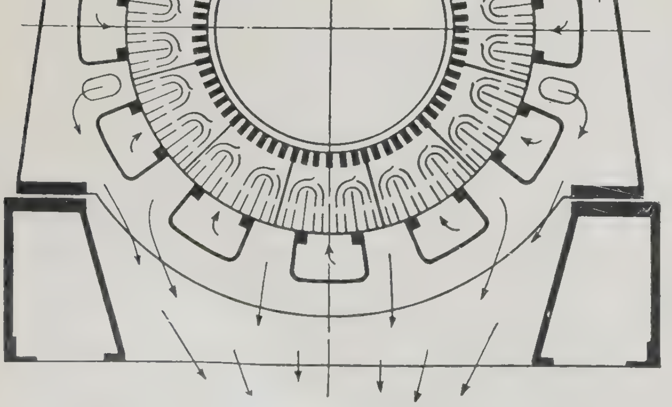


Fig. 5. Type of ventilation used on large machines

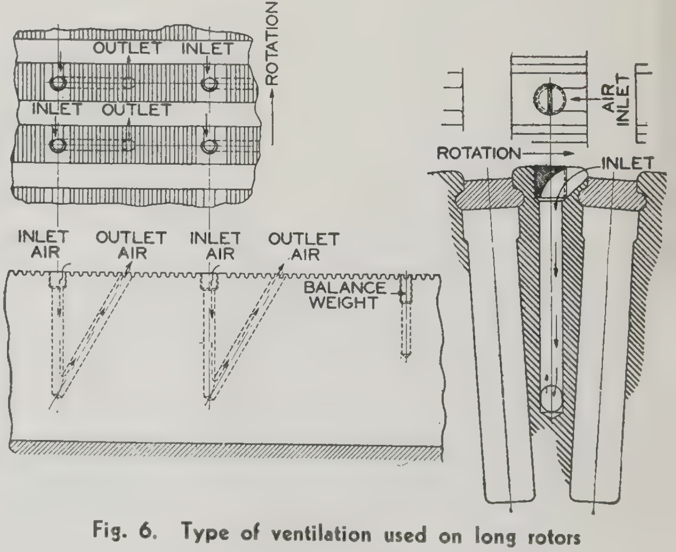


Fig. 6. Type of ventilation used on long rotors

dissipating capacities have been tested out at various times, frequently giving disappointing results which could have been foreseen with the aid of an analytical investigation. The rotor tooth ventilating scheme shown in figure 3 is used on rotors of short and medium lengths. Rotors of great axial length are ventilated as indicated in figure 6. With this scheme, the cylindrical radiating surface of the rotor is augmented with radial vent ducts in the rotor body. By special design, the entrance side of the duct produces an impact head, which forces air from the air gap through the ducts back into the air gap, from which it passes through the ventilating paths as indicated in figure 5. This type of ventilation has been satisfactory on rotors of lengths up to 283 inches and with peripheral velocities up to 26,000 feet per minute.

The importance of ventilating rotor coil ends has been recognized since the early days of turbogenerator construction. On present designs it is taken care of by means of ventilating ducts in the rotor coil support rings as well as in the portion of the rotor body adjoining the coil ends. The ventilating openings are located with the idea of obtaining high air velocities over the exposed coil ends and eliminating dead air pockets.

In conclusion I wish to reiterate that Peck's work is of practical value, not only in analyzing test results but also as a contribution to the further advances of the art of rotor design.

Transients in Magnetic Systems

Discussion of a paper by C. F. Wagner published in the March 1934 issue, pages 418–25, and presented for oral discussion at the electrical machinery session of the winter convention, New York, N. Y., January 22, 1935.

Ernst Weber (Brooklyn Polytechnic Institute, Brooklyn, N. Y.): This paper represents a valuable extension of the original treatise ("Field Transients in Magnetic Systems," Ernst Weber, A.I.E.E. TRANSACTIONS, volume 50, 1931, pages 1234–46) to cases where the relative amount of magnetomotive force expended on the solid section of the magnetic path is a large fraction of the total magnetic motive force in the magnetic circuit. This ratio is defined as

$$\mu = \frac{b}{a+b}$$

where $b = \frac{l_s}{\mu_s}$ and $a = \delta + \frac{l_l}{\mu_l}$ with l the length, μ the relative permeability, δ the length of the air gap, and subscripts s and l indicating the solid and laminated parts, respectively. Obviously μ will be large if a is much less than b, as when the air gap δ is very small and when μ_s is very small.

In the case of small air gaps, however, the fundamental assumption of Wagner, that the readjustment of the distorted magnetic flux, as present in the solid part, to uniform distribution in the laminated part shall occur in an infinitely thin layer of infinite permeability, cannot be true. It seems reasonable to assume that the transition to uniform distribution will be gradual and might occupy the whole air gap length so that, in fact, the true problem should

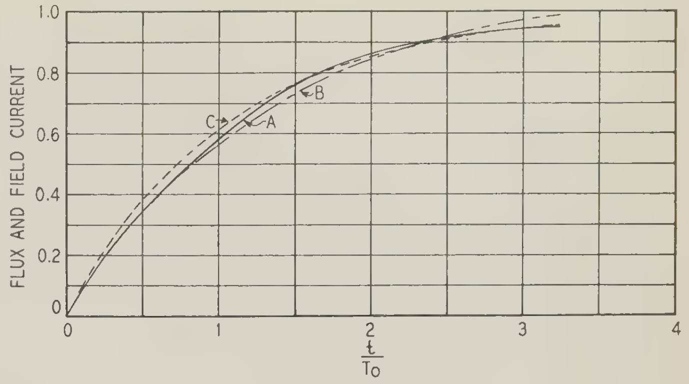


Fig. 1. Variation of total flux and field current as a function of t/T_0

A. Magnetic field flux ϕ from oscillogram

B. Exciting current i from oscillogram

C. Computed field transient

include the solution of the magnetic field distribution in the air gap with given boundary distributions on either side of the air gap. A vigorous solution of this problem would hardly be justified and from the small correction to be applied one can infer that the complete solution of the problem would give results somewhere between the values presented in the 2 papers. Large d-c machines, certain relay circuits, and possibly galvanometers might present magnetic circuits requiring the more involved treatment as given by Wagner, whereas the synchronous machine problems are, in general, adequately covered by the original theory.

To give an example, oscillograms have been taken on a smaller synchronous generator in the electrical laboratory of the Polytechnic Institute of Brooklyn. The 3-phase generator rated 7.5 kva at 110 volts per phase was driven by a d-c motor at synchronous speed with the field circuit switch open. At the instant of closing this switch the current induced in one of the stator phases, short circuited through a large resistance, and the current in the exciting winding were oscillographed simultaneously (see figure 1 of this discussion). From the curves a true time constant of the magnetic field could be evaluated as $T_\phi = 0.1486$ second. Computations from the known data of the generator lead to the following values: $T_0 = \frac{L_0}{R} = 0.144$ second, $T_s = 0.942$ second, and $\mu = 0.0341$. The small value of μ tends to indicate a very small deviation from the exponential curve for the magnetic field and a comparison with the computed curves in the paper by Wagner confirms this.

It is interesting now to contrast the value of the field time constant as given by equation 59 in the original paper with the experimental value given here. According to definition, $\theta = \mu T_s = 0.0353$ second and $\frac{\theta}{T_0} = 0.218$ so it follows that

$$T_\phi = T_0 + 0.12\theta = 0.144 + 0.0042 = 0.1482 \text{ second}$$

which is in very close agreement with the test. It seems, therefore, that it is quite possible to predict the time constant of complex magnetic circuits with fair accuracy if the air gap is comparatively large. Unfortunately Wagner does not arrive at a similar simple formula for the total magnetic time constant valid for small air gaps and showing the dependence on the ratio μ. This would be valuable for quick-excitation problems in large reversible d-c machines such as are used in mining and milling plants. (See "Wissenschaft Veroeff a. d. Siemens Konzern," E. Weber and H. Hess, 1930, volume 9, part 1, page 115.)

Expulsion Protective Gaps on 132 Kv Lines

Discussion of a paper by Philip Sporn and I. W. Gross published in the January 1935 issue, pages 66–73, and presented for oral discussion at the general overhead line problems session of the winter convention, New York, N. Y., January 23, 1935. Other discussions of this paper were published in the March 1935 issue, pages 329–32.

C. M. Foust (General Electric Co., Schenectady, N. Y.): The performance of the expulsion protective gaps is very interesting, and highly gratifying to those who have taken part in this forward looking experiment. As I have had the opportunity to follow closely the tower structure current measurements, such as given in table V, I am very interested in the use made of these measurements in arriving at tube currents such as given in column 4 of this table. I note that the authors have used the laws of traveling waves, assuming that the stroke current travels to the tower where it seeks various paths, in the line conductor, ground wire, and through the tower to ground. On this basis tube currents arrived at range from 11,000 to 37,000 amperes. The cases considered include only those wherein tower leg currents above 25,000 amperes were recorded. I also note the authors' opinion that the true tube currents may be only 1/2 the values given in the table.

Values of tube current may be arrived at by another method, as follows:

1. Calculate tower structure potential from tower footing resistance and tower leg current.
2. Take a conductor surge impedance in both directions such as 250 ohms and calculate tube current by dividing tower potential by this impedance.

I have worked out values using this method for all cases wherein the tower leg currents indicated direct strokes to towers.

The current values for the tubes obtained ranged from 450 amperes to 9,000 amperes, which range is about $^1/_3$ that given in table V. The average tower potential for single tube operation was 710 kilovolts, for 2 tube operation 970 kilovolts, and for all 3 tubes, top, middle, and bottom, 1,100 kilovolts. In the cases considered it is, of course, not certain that the stroke terminated on the tower; undoubtedly in some cases it reached the conductor. Such cases detract from the accuracy of this analysis. Again the use of the ordinary tower footing resistance measured at low voltage undoubtedly introduces errors. The true surge resistance at high current values should be used.

The correlation of tower currents with tube operations is very interesting. Again using only those towers at which the strokes appeared to terminate, current values ran as follows:

For top phase tube operation, tower currents ranged from 13,000 to 35,000 amperes, averaging 28,000 amperes.

For middle phase operation, tower currents ranged from 15,000 to 44,000 amperes, averaging 31,000 amperes.

For bottom phase operation, tower currents ranged from 23,000 to 49,000 amperes, averaging 36,000 amperes.

For top and middle phase operation, tower currents ranged from 30,000 amperes to 68,000 amperes, averaging 45,000 amperes.

For top and bottom phase operation, tower currents ranged from 28,000 to 30,000 amperes, averaging 29,000 amperes.

For middle and bottom phase operation, tower currents ranged from 38,500 to 52,000 amperes, averaging 45,000 amperes.

For top, middle, and bottom phase operation the tower currents ranged from 17,000 to 100,000 amperes, averaging 60,000 amperes.

The average tower current for single tube operation was 32,000 amperes; for 2 tube operation, 38,000 amperes; and for 3 tube operation 60,000 amperes.

More current measurements are required, particularly such measurements as might help to determine the correct method for determination of the tube currents.

P. L. Bellaschi (Westinghouse Elec. and Mfg. Co., Sharon, Pa.): The part lightning plays as a disturbing factor in the transmission and distribution of power is well known. To mitigate its effect has been the problem. In this respect field records of strokes of lightning near and at distribution transformers protected with deion gaps have furnished data. The electrodes of the deion gaps discharging the lightning current are marked with a surface figure which when compared with similar figures on deion gaps tested in the laboratory with known lightning currents, enables us to evaluate the lightning current discharged through the deion gap in service.

A record of lightning strokes near and at distribution transformers during 1932–33 is shown by the heavy line in figure 1 of this discussion. A direct stroke to the terminals of a transformer, which was recorded in 1934, indicated a current somewhat greater than 100,000 amperes. The dash-dot extension to 150,000 amperes in the figure is intended to represent the maximum current hereto recorded; however, this maximum value does not preclude the possibility of even 200,000 amperes in the more infrequent case of a very severe lightning stroke.

The lightning stroke current has also been evaluated from other physical effects manifested with the discharge, such as the fusion and crushing of conductors, the explosive action produced, etc. The currents evaluated in this way are well in accord with the values in figure 1.

The lightning stroke currents reported by Sporn and Gross in table V of their paper are interesting indeed. They are plotted in figure 2 of this discussion. It will be noted that the magnitude of the lightning stroke currents as established by the 2 sets of independent data in figures 1 and 2 are substantially the same. Furthermore, data on lightning currents presented at the A.I.E.E. Pacific Coast convention, September 1934, show similar distribution curves. Another interesting observation is the confirmation between the recent field data and the lightning stroke currents that have been calculated by C. L. Fortescue.

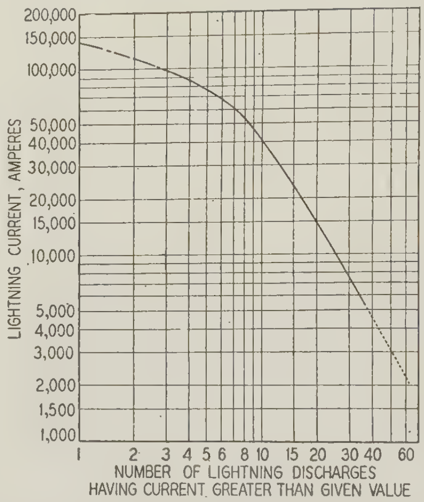


Fig. 1. Record of lightning strokes near and at distribution transformers during 1932–33

Transformer years = 4,000

The data on lightning presented by the authors are distinct contributions to the art of lightning protection. From the standpoint of the electrical engineer, perhaps the most important future work in the domain of lightning is to establish directly with the cathode ray oscillograph the amplitude and duration of the lightning stroke potential developed on electrical circuits. In all events, field experience will undoubtedly remain a most valuable source of information and in fact it alone can be the ultimate confirmation of the adequacy of the protective apparatus used.

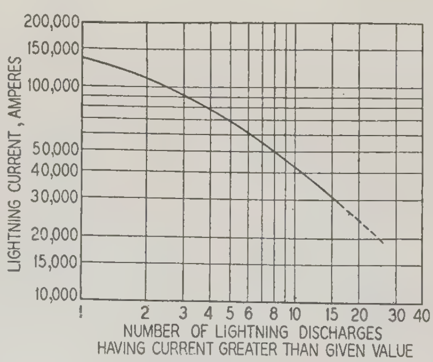


Fig. 2. Record of direct strokes of lightning to 132 kv transmission line

A Carrier Current Relay Installation

Authors' closing discussion of a paper published in the January 1935 issue, pages 109–15, and presented for oral discussion at the general overhead line problems session of the winter convention, New York, N. Y., January 23, 1935. Other discussions of this paper were published in the March 1935 issue, pages 333–4, and in the April 1935 issue, pages 445–6.

O. A. Browne and **W. L. Vest, Jr.** (both of Western Massachusetts Companies, Turners Falls and Springfield, respectively): A brief review of some of the existing conditions on this system will answer some of the questions raised in the discussion.

The lines on which the carrier controlled relays were installed were constructed between the years 1913–1918 inclusive, using double circuit steel towers. The spacing of the conductors is 8 and 9 feet, vertical. The insulation on approximately 80 per cent of the lines protected with the new relays is 4 and 5 standard 10 inch units, protected by arcing horns set with gaps of approximately 15 inches at suspension towers. One ground wire is used on all the towers. The insulation level is low enough to allow simultaneous flashover of both circuits from heavy induced lightning surges. From observations of relays and other equipment, the double circuit faults are generally simultaneous.

As a result of the location of these lines with respect to the large interconnected systems to the north and south, disturbances external to the system frequently caused unnecessary operations, thereby splitting the system. In order that these operations be kept at a minimum, high current and long time settings were required.

The new relay scheme was installed in May and June 1933, during the lightning season. This relay scheme was not tested with any artificial faults, as such a procedure was not practical on this system. The relays were expected to operate, and where incorrect relay operations occurred, the analysis of these operations would serve as a guide in correcting any troubles. Although this method is not conducive to the best operating record, it does have certain obvious advantages.

An analysis of the incorrect operations is shown in table I of this discussion. Generally, several incorrect operations would occur from the same cause before corrective measures could be made. It is quite common for the same section of line to trip out 3 to 5 times within an hour or so.

With the previous arrangement, surging and out-of-step conditions with the Connecticut system frequently occurred. During these occurrences the trouble would be cleared with the operation of the relays on the Hartford-Agawam lines, at either one

end or the other. These operations usually resulted in a drop in frequency on one of the 2 systems, dependent upon direction of load in the lines, and consequently some delay occurred before the systems could again be paralleled.

In the design of this relay scheme, no provision was made for controlled separation during out-of-step conditions, as it was believed that this situation would be vastly improved with the faster relays.

No change to a series or loop connection was made at any of the tap stations, as it was not considered desirable to transmit power across certain of the station busses. At stations such as Cobble Mountain there would be considerable line and voltage loss if the station were looped, particularly with the generators in service. However, cutting Amherst and Westfield into just one line as a loop station has been considered, as it will reduce outages to these stations when double circuit line faults occur in these sections.

The type *IAC* tripping relays were selected for use at the various sectionalizing stations as it would be possible to accurately predetermine the time and current values at which the relays would trip. At the tap stations, the *IDP* relays were chosen as being more sensitive both in current and time, although the values would be more difficult to predetermine, since the voltage restraint would be the deciding factor.

On the several tapped lines, it was considered desirable to allow 8 cycles time on the tripping relays at the ends of the line, and a somewhat lower setting at the tap stations, until some operating experience was obtained. The results obtained have been so good that, although the tripping time of the relays might be reduced somewhat, it is not absolutely necessary, and it does add somewhat to the hazard of incorrect operations.

Carrier current equipment was preferred over leased lines of the communications companies as it was considered desirable to have complete control of the pilot channel at all times. Also, many of the trunk communication lines in this area are of open wire construction. This is in no way any reflection on the quality of service now furnished us by the communication companies.

The dynamotor operating from the station battery was selected as the source of a constant supply alternating potential which could be used with a step-up transformer and rectifier to obtain the necessary direct potential. Alternating potential from the station service supply would be suitable, based on a voltage regulation standpoint, but would be subject to interruptions. In 2 years of operation, one failure of a dynamotor occurred, and this was not serious.

Although continuous carrier current systems are faster than those schemes used for blocking purposes only, the failure of the continuous system for any reason would result in unnecessary tripping.

All of the stations are protected with bus overload and ground protection. In addition, the phase overload relays act as transformer overload protection, and sufficient time is allowed to select with secondary feeders. The ground relay is set for a minimum current and time, dependent upon the type of relay used.

Table I—Analysis of Incorrect Relay Operations

Number of: Incorrect Operations	Number of: Failures to Operate	Cause
During 1933		
	6	Too sensitive a setting on *RCC* receiver relay
7	3	Incorrect connection of *ICC* and *ICP* ground relays
2		Improper co-ordination of the *ICC* relays at Cabot station with the *ICP* relays on the remainder of the system
1		Faulty relay adjustment
During 1934, to October 1		
9		Incorrect connection of a relay due to a panel change
9		Ground in current transformer
2		Improper co-ordination of the *ICC* relays at Cobble Mountain station with the *ICP* relays on the remainder of the system
2		Receiver relay failed to block tripping; cause unknown
	2	Cobble Mountain station shut down, no polarizing current in ground relays

The relays originally used for single circuit and double circuit protection at the sectionalized stations were left in service as back-up protection for the carrier relays. In some cases, the current settings were as high as 400 amperes (66 kv) each, per pair of circuits, or 800 amperes on the remaining circuit with one out of service and with time settings of 140 cycles at 10 times the above current settings.

Any relay scheme that the authors are familiar with requires the correct operation of all the relays on the system, for complete and successful protection. Of course, one must remember that "correct relay operation" often means no operation at all for a particular relay.

The M.I.T. Power Factor Bridge and Oil Cell

Discussion of a paper by J. C. Balsbaugh, N. D. Kenney, and Alfred Herzenberg published in the March 1935 issue, pages 272–9, and presented for oral discussion at the selected subjects session of the North Eastern District meeting, Worcester, Mass., May 16, 1934.

W. S. Baird (nonmember): The authors of this and the companion paper (Franklin Institute *Journal*, volume 49, 1934, page 218) have brought the Schering bridge to a degree of perfection, both in analysis and design, made necessary by the demand for precision in this most important field of research. The design of the component parts, the high voltage capacitors, and the cells, shows that due consideration has been given to all the factors recognized to be of influence when working in the specified range of power factor.

The change in the power factor of the oi cell as shown in figure 6 of their paper is not explained and the reason for such behavior is conducive to speculation. The fact that temperature error cannot be the cause, and the fact also that the power factor returned approximately to its original value seem to indicate that the cause lies in thermal expansion and subsequent cell deformation concurrent with such a heat cycle. That such may be the case and may cause considerable error if not taken into account has been shown recently in the paper by Whitehead and Greenfield (Electrical Engineering, October 1934, pages 1389–96, and November 1934, pages 1498–1503). While measuring the specific resistance of mercury in "pyrex" glass tubes and over the identical temperature range covered by the authors of the paper under discussion, the writer found looped curves and ascribed them to dimensional changes in the glass. After successive runs, it was found that the variation with increasing and decreasing temperatures became smaller, as is shown also by the curves of figure 6. This can be explained as a result of successive annealing cycles. From curve *D* of the figure and the authors' discussion, it is not clear whether the experimental points represent increasing or decreasing temperatures, or both. If curve *D* represents both the results of increasing and decreasing temperatures after heating by induction, an interesting light is thrown upon the mechanism which gives rise to power factors for air capacitors in the region 10^{-6} for which a satisfactory explanation has not yet been given.

In previous papers and indeed in the present paper, the authors have indicated that they believe power factors of air condensers in the region 10^{-6} are caused by films of oxide on the measuring surfaces. Such an oxide film would have to be of considerable thickness to give rise to a resistance sufficient to account for a power factor of this order of magnitude, since the loss must result from the flow of the displacement current over the film and the resistance of that film. It is the opinion of the writer that the power factor can be accounted for by the fact that the surface of the metal used to form the capacitors is not smooth, even though care is taken to clean it. Such a roughened surface would have innumerable points giving occasion for local regions of high stress, and a subsequent Joule heating through the point itself, i. e., from the tip, or point of high stress, to the base, or region of lower stress. This is equivalent to saying that the surface density of charge is not uniform with the consequences resulting therefrom. The only evidence at present available to substantiate this theory is taken from a curve of the authors in the Franklin Institute paper, which shows that after wetting the surface of a capacitor, the power factor showed a decrease; the wetting gave at first a surface smoother than that of the metal. In the present instance, heating by induction may have smoothed the surface in several ways. This suggestion is offered for what it may be worth.

Toward the end of the paper the statement is made, ". . . prevents the oil test sample from being injected into a vacuum." Is one to infer from this that the authors consider the injecting of oil into a vacuum a bad practice?

News

Of Institute and Related Activities

Program of the A.I.E.E. Summer Convention at Cornell University

A PROGRAM replete with activities of interest to the profession has been arranged for the 51st annual summer convention of the Institute to be held on the campus of Cornell University, Ithaca, N. Y., June 24–28, 1935. The annual business meeting, conference of officers, delegates, and members, board of directors' meeting, 10 technical sessions, and a number of technical conferences assure a busy and profitable week for those who wish to keep pace with Institute affairs and the progress of the art. Also, sports, trips, and recreation, as well as entertainment for the visiting women, have not been overlooked. The evenings will be devoted mainly to social functions. All these activities are offered to members and guests at a very reasonable cost, made possible by the splendid facilities which Cornell University affords in a beautiful scenic setting. A large attendance is expected.

Of interest to some members of the Institute is the fact that during the latter part of the week immediately preceding the convention at Ithaca, the semi-annual meeting of The American Society of Mechanical Engineers will be held in Cincinnati, Ohio, June 19–21, 1935. Technical papers on a variety of subjects will be presented at the A.S.M.E. meeting, and a side trip to Norris Dam is scheduled by the A.S.M.E. for June 22. Members making this inspection trip should be able to arrive at Ithaca in time for the beginning of the A.I.E.E. meeting.

The general schedule of events for the A.I.E.E. convention is given below. Details of technical sessions, technical conferences, entertainment, inspection trips, sports, and other features are given in other parts of this article.

Summarized Schedule of Events

Eastern standard time is used in Ithaca throughout the year.

Monday, June 24

8:30 a.m.—Registration
10:00 a.m.—Opening of Convention
- Address of welcome: Dr. A. R. Mann, provost, Cornell University
- Annual Business Meeting of the Institute
  - Annual report of board of directors, in abstract, by H. H. Henline, national secretary
  - Report of committee of tellers on: (*a*) election of officers; (*b*) constitutional amendments
- Introduction of and response from president-elect
- Presentation of prizes for papers
- Presentation of Lamme medal to Henry E. Warren
- President's address: J. Allen Johnson

11:30 a.m. Conference of Officers, Delegates, and Members
1:00 p.m.—Lunch
2:00 p.m.—Conference of Officers, Delegates, and Members (continued)
2:00 p.m.—Technical Conferences
8:00 p.m.—President's Reception

Tuesday, June 25

9:00 a.m.—Instruments and Measurements Session
Power Generation Session
11:30 a.m.—Lecture
1:00 p.m.—Lunch
2:00 p.m.—Conference of Officers, Delegates, and Members (continued)
Technical Conferences
2:00–4:30 p.m.—Cars will leave campus for an outing to Taughannock State Park
5:30 p.m.—Shore Dinner at Taughannock
8:30 p.m.—Lecture

Wednesday, June 26

9:00 a.m.—Start of womens' trip to Corning Glass Works. Luncheon either in Corning or Watkins, followed by bridge or other entertainment
9:00 a.m.—Electrical Machinery Session—I
Protective Devices Session
Education Session
11:30 a.m.—Directors' luncheon meeting
9:00–2:30 p.m.—Cars will leave the campus for an inspection trip to the Corning Glass Works
Buffet supper at Corning

Thursday, June 27

9:00 a.m.—Electrical Machinery Session—II
Applications to Iron and Steel Production Session
Selected Subjects Session
11:30 a.m.—Lecture
2:00 p.m.—Technical Conferences
7:00 p.m.—Convention banquet; dancing

Friday, June 28

9:00 a.m.—Electrochemistry and Electrometallurgy Session
Power Transmission Session
12:00 Noon—Windup luncheon

Technical Sessions

A number of timely technical papers which have to do with some of the most recent developments will be presented in an enlarged program comprised of 10 technical sessions. The Boulder Canyon project will be quite thoroughly described by a series of papers to be presented in the sessions on power generation, power transmission, and protective devices. The hydroelectric construction will be given in a paper by L. C. McClellan, chief electrical engineer, U.S. Bureau of Reclamation, Denver, Colo. Some general features as well as the engineering features of the project and of the transmission system from Boulder Dam to the City of Los Angeles, will be given in 2 papers by E. F. Scattergood, Bureau of Power and Light, Los Angeles, Calif. Still another paper by D. C. Prince, General Electric Company, Philadelphia, Pa., will treat the theory, construction, and testing of the large 287 kv circuit breakers for this line. In addition, 7 other technical sessions embrace many valuable papers which will present the latest theories, designs, and researches in the following fields: instruments and measurements, electrical machinery (2 sessions), applications to iron and steel production, electrochemistry and electrometallurgy, education, and selected subjects.

In the technical program which follows, it may be noted that for the papers which already have been published, reference is given after the title to the issue and page of ELECTRICAL ENGINEERING publication. Remaining papers are scheduled for publication in the June issue. The availability of many of the papers considerably in advance of the convention will permit the careful preparation of discussion. Thus those who attend the sessions will be assured of hearing many pertinent discussions by engineers who are well known in their respective fields of endeavor.

RULES ON PRESENTING AND DISCUSSING PAPERS

At some of the technical sessions, a few papers may be presented only by title. This will permit the devotion of more time to discussion. At other sessions, papers will be presented in abstract, 10 minutes being allowed for each paper unless otherwise arranged, or the presiding officer meets with the authors preceding the session to arrange the order of presentation and allotment of time for papers and discussion. Authors will be notified officially in each case about one month in advance.

Any member is free to discuss any paper when the meeting is thrown open for general discussion. Usually 5 minutes are allowed

Technical Program

Tuesday, June 25

9:00 a.m.—Instruments and Measurements, W. B. Kouwenhoven, *chairman*

Precise Speed Control for D-C Machines, R. H. Frazier and J. Eisler, Massachusetts Institute of Technology, and W. P. Frantz, Curtis Publishing Company. March issue, p. 307–12

Definitions of Power and Related Quantities, H. L. Curtis and F. B. Silsbee, Bureau of Standards. April issue, p. 394–404

Direct Measurement of Surge Currents, C. M. Foust and J. T. Henderson, General Electric Co. April issue, p. 373–78

An Improved Electrothermic Instrument, P. M. Lincoln, Cornell University. May issue, p. 474–81

Lubrication Increases Life of Meter Bearings, T. A. Abbott and J. H. Goss, General Electric Co. April issue, p. 428–31

9:00 a.m.—Power Generation, H. W. Leitch, *chairman*

Engineering Features of Boulder Dam and Power Plant, L. N. McClellan, U. S. Bureau of Reclamation. Scheduled for June issue

Design and Operation of Huntley Station No. 2, H. M. Cushing, Buffalo General Electric Co. Scheduled for June issue

Rehabilitation of the Connors Creek Power Plant, R. E. Greene, Detroit Edison Co. Scheduled for June issue

Wednesday, June 26

9:00 a.m.—Electrical Machinery—I, V. M. Montsinger, *chairman*

An Analysis of the Induction Motor, S. J. Levine, General Electric Co. May issue, p. 526–9

Capacitive Excitation for Induction Generators, E. D. Bassett, F. W. Sickles Co., and F. M. Potter, General Electric Co. May issue, p. 540–5

Sparking Under Brushes of Commutator Machines, R. E. Hellmund and L. R. Ludwig, Westinghouse Electric and Mfg. Co. March issue, p. 315–21

Time-Temperature Tests to Determine Machine Losses, M. D. Ross, Westinghouse Electric and Mfg. Co. May issue, p. 512–5

9:00 a.m.—Protective Devices, H. P. Sleeper, *chairman*

Oil Circuit Breaker and Voltage Recovery Tests, E. J. Poitras, Ford Instrument Co., H. P. Kuehni and W. F. Skeats, General Electric Co. Feb. issue, p. 170–8

Breaker Performance Studied by Cathode Ray Oscillograms, R. C. Van Sickle, Westinghouse Electric and Mfg. Co. Feb. issue, p. 178–84

Circuit Breakers for Boulder Dam Line, D. C. Prince, General Electric Co. April issue, p. 366–72

The Determination of Circuit Recovery Rates, E. W. Boehne, General Electric Co. May issue, p. 530–9

Surge Currents in Protective Devices, A. M. Opshal, Westinghouse Electric and Mfg. Co. Feb. issue, p. 200–4

Fault and Out-of-Step Protection of Lines, H. D. Braley, The New York Edison Co., and J. L. Harvey, New York Power and Light Co. Feb. issue, p. 189–200

9:00 a.m.—Education, L. A. Doggett, *chairman*

An Advanced Course in Engineering, A. R. Stevenson, Jr., and Alan Howard, General Electric Co. March issue, p. 265–8

Possibly another paper.

Thursday, June 27

9:00 a.m.—Electrical Machinery—II, V. M. Montsinger, *chairman*

A Stroboscopic Power-Angle Recorder H. E. Edgerton, Massachusetts Institute of Technology. May issue, p. 485–8

Armature Leakage Reactance of Synchronous Machines, L. A. March and S. B. Crary, General Electric Co. April issue, p. 378–81

Transient Voltages in Rotating Machines, E. M. Hunter, General Electric Co. Scheduled for June issue

Saturated Synchronous Reactance, Charles Kingsley, Jr., Massachusetts Institute of Technology. March issue, p. 300–5

Insulation for High Voltage Alternators, C. M. Laffoon and J. F. Calvert, Westinghouse Electric and Mfg. Co. Scheduled for June issue

Effects of Saturation on Machine Reactances, L. A. Kilgore, Westinghouse Electric and Mfg. Co. May issue, p. 545–50

9:00 a.m.—Applications to Iron and Steel Production, R. W. Graham, *chairman*

D-C Braking of Induction Motors, F. E. Harrell and W. R. Hough, The Reliance Electric and Engineering Co. May issue, p. 488–93

Speed Transients of D-C Rolling Mill Motors, L. A. Umansky and T. M. Linville, General Electric Co. April issue, p. 387–4

Electric Power Equipment for Steel Plants, R. H. Wright, Westinghouse Electric and Mfg. Co. May issue, p. 481–5

D-C Circuit Breakers in Steel Mill Service, William Deans, I-T-E Circuit Breaker Co. Scheduled for June issue

9:00 a.m.—Selected Subjects, H. M. Turner, *chairman*

Protective Signaling, P. M. Farmer, American District Telegraph Co. Scheduled for June issue

D-C Clean-Up-In Insulating Oils, J. B. Whitehead and S. H. Shevki, The Johns Hopkins University. Scheduled for June issue

The Sparkless Sphere Gap Voltmeter, R. W. Sorensen, J. E. Hopson, and Simon Ramo, California Institute of Technology. Scheduled for June issue

Friday, June 28

9:00 a.m.—Electrochemistry and Electrometallurgy, N. R. Stansel, *chairman*

Opening Address.

Calculations for Coreless Induction Furnaces, H. B. Dwight, Massachusetts Institute of Technology, and M. M. Bagai, Ampere, N. J. March issue, p. 312–5

Storage Battery Charging, J. L. Woodbridge, The Electric Storage Battery Co. May issue, p. 516–25

Photoelectric Control of Resistance Type Metal Heaters, E. H. Vedder, Westinghouse Electric and Mfg. Co., and M. S. Evans, American Car and Foundry Co. Scheduled for June issue

Address: The Electrochemical and Electrometallurgical Industries in Japan, D. Takei, Tokyo University of Engineering.

9:00 a.m.—Power Transmission, D. M. Simmons, *chairman*

Some Features of the Boulder Canyon Project, E. F. Scattergood, Bureau of Power and Light, City of Los Angeles. April issue, p. 361–5

Engineering Features of the Boulder Dam Transmission System, E. F. Scattergood, Bureau of Power and Light, City of Los Angeles. May issue, p. 494–512

A Criterion of Quality of Cable Insulation, K. S. Wyatt and E. W. Spring, The Detroit Edison Co. April issue, p. 417–21

to each discusser for the discussion of a single paper or of several papers on the same general subject. When a member signifies his desire to discuss several papers not dealing with the same general subject, he may be permitted a somewhat longer time.

It is preferable that a member who wishes to discuss a paper give his name in advance to the presiding officer of the session at which the paper is to be presented. Each discusser is to step to the front of the room and announce, so that all may hear, his name and professional affiliations. Three typewritten copies of discussion prepared in advance should be left with the presiding officer.

Other discussion to be considered for publication must be submitted, typed double spaced, in triplicate to C. S. Rich, secretary of the technical program committee, A.I.E.E. headquarters, 33 West 39th St., New York, N. Y., on or before July 12, 1935. Discussion received after this date will not be accepted.

Technical Conferences

A number of technical conferences or informal round table meetings on various subjects have been scheduled for the benefit of specialists and the younger members. At some of these meetings leaders in specialized fields will speak informally pointing out the lines of future progress as they see them, after which those attending should feel free to discuss subjects on the agenda informally. It is hoped that these talks will direct some of the work of the Institute committees into new and pertinent channels. No provision will be made for printing of talks, papers, discussions, or conclusions reached at these conferences.

The objectives and agenda for several of the technical conferences are described in the paragraphs which follow the "Schedule of Technical Conferences" given below.

Schedule of Technical Conferences

Monday, June 24, 2:00 p.m.

Problems of the Student and Cadet Engineer, M. G. Malti, *chairman*.

D-C Test Code, R. W. Owens, *chairman*.

Transformers, J. E. Clem, *chairman*.

Research on Insulating Oils, K. S. Wyatt, *chairman*.

Tuesday, June 25, 2:00 p.m.

Noise, P. L. Alger, *chairman*.

Mercury Arc Rectifiers, O. K. Marti, *chairman*.

Dielectric Theories, H. H. Race, *chairman*.

Circuit Breaker Standards, H. P. Sleeper, *chairman*.

Reactance Coefficients of Synchronous Machines, C. M. Laffoon, *chairman*.

Thursday, June 27, 2:00 p.m.

Electrical Engineering Curricula and Educational Methods, H. W. Bibber, *chairman*.

Research in Engineering Schools, Vladimir Karapetoff, *chairman*.

Distribution Transformer Protection, K. B. McEachron, *chairman*.

Tensor Analysis, E. E. Dreese, *chairman*.

Conductor Vibration, D. M. Simmons, *chairman*.

In some cases members are invited to submit discussions to the respective chairmen in advance of the meetings. In general, the conferences have been sponsored by the subcommittees of technical committees and they afford an opportunity for the committees to obtain assistance from individuals, not members of the committees, but interested in the particular subjects under discussion. In this way both the individuals and the committees will profit.

Problems of the Student and Cadet Engineer

Of interest to students, educators, and personnel directors is the technical conference devoted particularly to the problems of the student and cadet engineer. Professor Malti has, for the past 2 months, been sounding educational and professional opinion as to how this round table discussion may be made most beneficial to students. He promises to give those who attend a cross section of the views regarding problems of students and cadet engineers. There will be short 10 minute talks by men in the industry and in the universities as well as by the students themselves. The purpose of these talks is to stimulate discussion rather than express dogmatic opinions. The speakers and subjects for this meeting will be announced in the June issue of Electrical Engineering. Watch for it!

D-C Test Code

The meeting will be opened by the chairman who will give a brief statement as to the history and purpose of the test code. Members of the subcommittee will discuss assigned topics as follows: judging of commutation, running-light losses, shaft currents, temperature test, brush setting insulation resistance, and stray load losses.

Noise

The discussion at this meeting will bring out available information on the levels of noise now existing under different living conditions in different places and psychological data on the desirable or "comfort" levels of noise which may reasonably be sought for in the future.

The availability of improved noise meters and measurement standards now enables noise levels to be determined and described accurately. This fact, together with the growing public demand for quieter apparatus, has greatly stimulated interest among electrical engineers in the subject of noise control. From the ideas developed at this meeting, it is hoped that designers will secure an improved understanding of what will constitute satisfactory noise levels in the future, and engineers generally will learn much about the practical aspects of noise measurement.

Informal talks will be given by 4 men who are noted for their leadership in the field of acoustics and noise measurements. Dr. Donald A. Laird, of Colgate University, will speak on the psychological aspects of noise; Dr. E. E. Free, of the E. E. Free Laboratories, New York, N. Y., will present the results of his experience in conducting over 100 noise surveys; John S. Parkinson, of the Johns-Manville Research Laboratory, will give his experiences in regard to the establishment of satisfactory levels of noise; and H. B. Marvin, of the General Electric Company, will speak on noise measurements with particular reference to electrical apparatus. Advance information may be secured by addressing the subcommittee chairman, P. L. Alger, General Electric Company, Schenectady, N. Y., or any one of the speakers.

Baker chemical laboratory on the campus of Cornell University, Ithaca, N. Y., where many of the technical sessions and round table discussions during the Institute's 1935 summer convention June 24–28, will be held

Mercury Arc Rectifiers and Inverters

At this conference prominent engineers will express their views on various subjects now being actively studied regarding this type of equipment. Among the topics to be discussed are: (1) water cooling, with its attendant phenomena of corrosion, and remedies for the latter; (2) interference with communication circuits due to harmonics produced in the a-c supply circuits, and means for their suppression or elimination; (3) voltage control by means of control grids, inversion, and regeneration; (4) consideration of terms such as thyratron, ignitron, and mutator, in view of the widening field of application of grid-controlled mercury arc rectifiers as inverters, frequency changers, commutators, etc.; and (5) the proposed A.I.E.E. Standards for dielectric tests, with particular reference to the recent use of mercury arc rectifiers for high voltage applications. It is felt that such a discussion will prove of benefit to all engineers taking part in it, who are interested in this increasingly important field.

Reactance Coefficients of Synchronous Machines

The discussion at this conference will cover definitions, effects of saturation, application, and methods of measuring reactances. Interested engineers are invited to submit discussions of this subject in advance of the meeting to C. M. Laffoon, chairman, synchronous machinery subcommittee, Westinghouse Electric and Manufacturing Company, E. Pittsburgh, Pa.

Electrical Engineering Curricula and Educational Methods

The list of speakers introducing the topics to be considered at this conference will be brief, in order that those attending may have an opportunity to express their personal views. An endeavor will be made to hold the discussion within the field of curricula and methods. It is hoped that the absence of any printed papers or reports of the discussion will result in speakers omitting many of the qualifying phases which frequently take the life out of a printed paper, so that bold and vigorous statements of views will be the rule. There has been no dearth of recent periodical literature dealing with questions of curricula and methods, and Dr. W. E. Wickenden's final report on the S.P.E.E. investigation of engineering education provides much interesting material for discussion.

Circuit Breaker Standards

This conference will consist of a discussion of the effect of recovery voltage and whether it should be included in the standard definition of interrupting rating, also a discussion of the differences between American and European circuit breaker standards.

Distribution Transformer Protection

This conference will consider the methods of protection of distribution transformers with particular reference to those in rural service, covering such items as interconnection of primary and secondary neutrals, grounding of transformer tanks, use of protective gaps, etc.

Tensor Analysis

Those interested in new theoretical developments should find this conference of unusual interest. Tensor analysis, as a branch of mathematics, has long been known to mathematicians. In late years this mathematical tool has been extensively employed by the physicists, particularly in dealing with relativity. Only recently has tensor analysis been applied with any vigor and success to electrical engineering. It now appears that the methods of tensor analysis give promise to the electrical engineer of simplicity of expression and generalization of heretofore divergent sub-

jects. This theoretical contribution appears to those electrical engineers familiar with it, to be important and significant in the treatment of circuits, electrical machinery, and the electron tube. It is the purpose of this conference to sound out not only these theoretical possibilities of simplification and generalization, but also to appraise, as well as can be done at this time, the practical significance and advantages of this new analysis in electrical engineering problems.

The application of tensor analysis to electrical engineering problems has nothing to do with relativity or relativity dynamics. It has simply been discovered that when the electrical engineer attacks the electrical machine using tensor analysis as a tool, he reaches a generalized equation which is of the same *form* as the equation reached by Doctor Einstein when he attacked the problem of relativity by the use of tensor analysis. This leads those versed in the subject to conclude that there is in the electrical machine a concrete physical analogue of the electron in motion.

Other Features

Entertainment

The entertainment features will consist of the President's reception and dance on Monday evening, an outing and picnic at Taughannock State Park on Tuesday afternoon, an inspection trip to the Corning Glass Works and buffet supper at Corning on Wednesday, an annual banquet and entertainment on Thursday, and a get-together luncheon on Friday.

In addition to the above, for the women there will be a drive about the Cornell campus, an inspection of the Home Economics College and laboratories, a drive to Enfield State Park, and a bridge luncheon. There will also be a musicale on Wednesday evening, at which Professor Karapetoff will be one of the entertainers. The committee is also making arrangements for 3 lectures by well known leaders in their respective fields.

Notice of Annual Meeting

The annual meeting of the American Institute of Electrical Engineers will be held at Cornell University, Ithaca, N. Y., at 10 a.m. on Monday, June 24, 1935. This will constitute one session of the annual summer convention which is to be held this year in Ithaca, N. Y.

At this meeting, the annual report of the board of directors, and the reports of the committee of tellers on the ballots cast for the election of officers and for constitutional amendments will be presented.

Such other business, if any, as properly may come before the annual business meeting may be considered.

(Signed) H. H. Henline
National Secretary

It will be necessary to charge moderate fees for certain entertainment events but the total amount of the fees for all events will not exceed $6 per person.

Taughannock State Park

There will be a picnic for all members of the A.I.E.E. and their guests on Tuesday afternoon, June 24. Taughannock Boulevard, skirting the western shore of Cayuga Lake, northward, 11 miles from Ithaca, leads to Taughannock State Park, where plunges Taughannock Falls, 215 feet high, the highest straight falls east of the Rocky Mountains. The park contains a bathhouse, shelter pavilion, excellent bathing beach, trails, baseball diamond, children's playground apparatus, bowling green, tennis courts, quoits, and horseshow pitching courts, camping and picnic facilities, as well as large parking areas, sight-seeing boulevards, outlooks, bridges, and other advantages. The cool breezes across Cayuga Lake constantly fan the 400 acres in the preserve.

Program

2:00–4:30 p.m.—Cars will leave campus at convenience of guests. Transportation will be provided for those who do not drive their own cars.

Entertainment at the Park—Trip through gorge to main falls; about one mile of scenic paths easy to travel. About one hour should be allowed for return trip. No guides necessary. Form your own party and take your time.

Sports on playground near the lake—Baseball (soft ball); Horseshow pitching; Bowling.

Swimming—Dressing rooms at State Park Pavilion may be used.

5:30 p.m.—Picnic supper served along lake front.

7:00–7:30 p.m.—Return to Ithaca in time for lecture at Bailey Hall.

Corning Glass Works

The main plants of the Corning Glass Works, the world's largest manufacturers of technical glassware, are located in Corning, N. Y., about 40 miles from Ithaca. Here was poured the famous 200 inch astronomical mirror for the California Institute of Technology, the production equipment for which may be inspected, as well as the manufacture of many products for scientific and general use. The company specializes in the manufacture of well-known brands of borosilicate and other technical glasses. Some of the products which may be in the course of manufacture during the inspection trips are: insulators; ovenware; chemical and laboratory ware; and railroad, marine and aviation signal glassware. Processes to be witnessed include the drawing of thermometer tubing, hand and machine drawing of tubing for neon signs, electric light bulbs, automobile fuses, gage glasses, etc., and also the manufacture of miscellaneous industrial wares. Of interest to the women will be the hand production of the famous "Steuben" art glass, such as vases, goblets, bowls, etc. A showroom is maintained for the display of some of the many thousands of items manufactured by this company.

At Wellsboro, Pa., about 40 miles from Corning, is another plant which will be open for inspection, where the high speed machine production of electric light bulbs and radio tube bulbs may be observed.

Principally for the women, the trip will start at 9:00 a.m. from Willard Straight Hall on Wednesday, June 26, and transportation will be available for the men attending the sessions from 9:00 a.m. to 2:30 p.m. in groups of 4 or 5 persons.

Future AIEE Meetings

Summer Convention,
Ithaca, N. Y., June 24–28, 1935

Pacific Coast Convention,
Seattle, Wash., Aug. 27–30, 1935

Great Lakes District Meeting,
West Lafayette, Ind., Oct. 24–25,1935

Winter Convention,
New York, N. Y., Jan. 28–31, 1936

North Eastern District Meeting,
New Haven, Conn., May 1936

Summer Convention,
Los Angeles, Calif., June 22–26, 1936

Middle Eastern District Meeting,
Akron, Ohio (date to be determined)

Sports

Golf, tennis, and swimming may be enjoyed at any time during the convention.

Golf—The Ithaca Golf Course, overlooking Cayuga Lake, is located just outside the campus and is one of the best courses in the Finger Lakes region. Arrangements have been made so that all guests can use this course on the payment of green fees of $1 per day. Other courses in this region will also be available.

The usual competition for the Mershon and Lee golf trophies will be held. The Mershon trophy is competed for on a match play handicap basis. The qualifying round for the Mershon trophy must be played on Monday, June 24; the second round, best 16, match play, will be played on Tuesday, followed by the third round on Wednesday, and the semi-final and final rounds on Thursday.

The Lee trophy is awarded annually for the lowest net score for 36 holes, of which the first 18 may be the qualifying round and the other 18 must be played not later than Thursday afternoon.

Other contests, including a putting contest for the women, will be held.

Tennis—The contests will center, as usual, about the Mershon tennis trophy which, beginning this year, is to be on a new basis. Instead of becoming the property of one who wins twice, it is to remain permanently in the possession of the Institute. The name of the winner will be engraved on it each year. The first contests in men's singles will be started on Monday, June 24.

Contests in men's doubles, women's singles, and mixed doubles will also be arranged if there is sufficient registration for them. Prizes for the winners will be awarded for these contests. There are plenty of courts available on the campus for all who desire to play whether competing for prizes or not.

Swimming—There are many natural outdoor swimming places about Ithaca, one of which is located in Fall Creek Gorge

Membership—

Mr. Institute Member:

Shortly after the time this message is placed in your hands you will receive a letter in the interest of membership activities asking that you send in the name of one person who, you feel, should be invited to join the Institute. Your helpfulness in this regard in the past has been the means of receiving many applications for membership and we know you will want to continue to help in this regard as in the past.

Chairman National Membership Committee

only a few minutes walk from the dormitories.

Walking and Driving—Ithaca is noted for its many gorges and beautiful walks. There are 2 gorges on the campus in which the outdoor enthusiast can spend many hours. There are also within a short driving distance many other beauty spots including: Buttermilk Falls and Gorge, 2 miles; Enfield Park and Gorge, 6 miles; Watkins Glen and Gorge, 30 miles. Directions to reach these will be available at the registration desk.

HOUSING

Living accommodations will be largely confined to the university dormitories located on the Campus. These are modern in all respects and while they do not have rooms with private baths, the accommodations are very comfortable. The rates charged at university dormitories are:

$2.00 per day per person for first 2 days
$1.00 per day per person after first 2 days

Dormitory reservations should be made in advance with L. A. Burckmyer, Cornell University, Ithaca, N. Y., chairman of the housing committee.

During the convention, good meals may be obtained economically in the cafeteria and dining rooms of Willard Straight Hall.

Private rooming houses adjoining the campus offer accommodations as follows:

$1.00 to $1.50 per day per person

Reservations also can be obtained at the hotels. Rates, European plan, are as follows:

Ithaca Hotel; 125 rooms, 75 with bath

	Per Day
Single rooms without bath	$2.00
Double rooms without bath	3.00 and $4.00
Single rooms with bath	2.50 and $3.00
Double rooms with bath	5.00 and $6.00

Clinton House; 60 rooms

	Per Day
Single room without bath	$2.00
Double room without bath	4.00
Single room with bath	2.50 and $3.00
Double room with bath	5.00 and $6.00

These hotels are at the foot of the hill about one mile from campus headquarters.

Glenwood Hotel on Cayuga Lake, about 4 miles from campus headquarters, will accommodate 75 people in the hotel and cottages. There is a good road along the lake shore to Glenwood. Reasonable rates may be obtained on either the American plan or the European plan.

Members and guests should make their hotel reservations by writing directly to the hotel of their preference.

Camping facilities may be found in a number of places, but the most desirable is at Taughannock State Park about 11 miles from Ithaca, and can be reached by good roads.

REDUCED RAILROAD RATES

Fare and one-third for the round trip over the same route will be available to members and guests, provided 100 certificates are validated at the registration desk. Consult your local ticket agent regarding the territory and dates applicable. Obtain your certificate authorized by the railroad passenger associations.

CAMPUS HEADQUARTERS AND REGISTRATION

The campus headquarters will be Willard Straight Hall, which is located on Central Avenue on the Cornell campus. The Cornell campus, one of the most beautiful in America, is situated on a hill overlooking the City of Ithaca and Cayuga Lake and may be reached from the depots by street car or bus (fare 10 cents), or by taxi (fare generally 50 cents). The registration bureau will open at 8:30 Monday morning and those in attendance should register promptly. A registration fee of $2.00 will be charged all nonmembers, except Enrolled Students and the immediate families of members.

COMMITTEE

The general convention committee for the 1935 summer convention consists of the following members: R. F. Chamberlain, *chairman;* W. H. Timbie, *vice-chairman;* A. C. Stevens, *secretary-treasurer;* P. L. Alger, C. H. Bissell, R. N. Conwell, E. P. Harder, V. Karapetoff, P. M. Lincoln, True McLean, W. E. Meserve, A. C. Stallman, I. Melville Stein, J. O. West, and J. P. Wood; also the following subcommittee chairmen: registration, E. M. Strong; housing, L. A. Burckmyer, Jr.; publicity, M. G. Malti; transportation, B. K. Northrop; inspection trips, J. T. Littleton; entertainment, W. C. Ballard, Jr.; and women's committee, Mrs. R. F. Chamberlain.

South West District Meeting Well Attended

Reports of the opening day of the A.I.E.E. South West District meeting held in Oklahoma City, Okla., April 24–26, received in time for inclusion in this issue, indicate a successful meeting. Registration for the first day exceeded 350 members, Students, and guests, and was drawn from 13 states. Attendance at the first 2 technical sessions averaged more than 300 persons each, and the wide discussion of the papers presented at these sessions reflects active interest.

A full report of this meeting is scheduled for publication in the June issue of ELECTRICAL ENGINEERING.

A.I.E.E. Executive Committee Meets

In accordance with action of the board of directors in October 1934, a meeting of the executive committee of the A.I.E.E. was held at Institute headquarters, New York, N. Y., on March 29, 1935.

In the absence of President Johnson, due to illness, Vice-President R. H. Tapscott presided, and the other members of the committee present were H. P. Charlesworth, F. Malcolm Farmer, Everett S. Lee, W. I. Slichter; also present were L. W. W. Morrow, a member of the board of directors, and National Secretary H. H. Henline.

A resolution in memory of Dr. Michael I. Pupin, Honorary Member and past president of the Institute, who died on March 12, was adopted, as printed elsewhere in this issue.

Reports were presented and approved of meetings of the board of examiners held February 19 and March 21, 1935; and upon the recommendation of the board of examiners, the following actions were taken: 2 applicants were transferred to the grade of Member; 12 applicants were elected and 13 transferred to the grade of Member; 76 applicants were elected to the grade of Associate; 205 Students were enrolled.

The finance committee reported monthly disbursements amounting to $24,089.39 in February and $17,009.87 in March. Report approved.

Upon request of the Southern Virginia

Section, the name of that Section was changed to "Virginia Section," inasmuch as its territory includes a large part of the state.

Upon the recommendation of the standards committee and subject to concurrence by the American Standards Association, the Association de Ingenieros del I.C.A.I. was granted permission to reprint A.I.E.E. Standards in Spanish.

Report was made of the following appointments made upon the recommendation of the standards committee: E. F. Beck as one of the Institute's representatives upon the Sectional Committee on Safety Code for Lightning Protection, and W. M. Dann as an alternate representative upon the Sectional Committee on Transformers.

The president's appointment of the following committee of tellers to canvass and report upon the ballots cast for the 1935 election of Institute officers and for the proposed constitutional amendments was confirmed: R. H. Twiss, *chairman*, J. T. Binford, W. E. Coover, K. B. Hoffman, Henry Kurz, H. F. Marples, and R. B. Shanck.

F. M. Farmer, chairman of the Institute's committee on research, was nominated for election as a representative of the Institute upon the Engineering Foundation board for the 4 year term beginning in October 1935, succeeding Dr. C. E. Skinner, whose term will expire at that time.

Dr. J. B. Whitehead was nominated for appointment as a representative of the Institute upon the division of engineering and industrial research, National Research Council, for the 3 year term beginning July 1, 1935, to succeed Chester W. Rice, whose term expires at that time.

Approval was given to the disbanding of the American Committee on Electrolysis after distribution of its assets among the organizations comprising the committee.

Announcement was made of a joint dinner meeting to be held at the Engineers' Club, New York, N. Y., on May 20, 1935, of the members of the governing bodies of the founder societies, United Engineering Trustees, Inc., and all joint organizations of these societies, for a comprehensive discussion of all joint activities.

Other matters were discussed, reference to which may be found in this or future issues of ELECTRICAL ENGINEERING.

Pacific Coast Convention Now Being Planned

Plans are taking form for the A.I.E.E. 1935 Pacific Coast convention, which will be held in Seattle, Wash., August 27–30. The Olympic Hotel will be convention headquarters. The tentative plans call for 5 technical sessions and 2 student sessions with social activities scheduled in the evenings.

The personnel of the Pacific Coast convention committee was announced in ELECTRICAL ENGINEERING for April 1935, page 451. The names of the chairmen of the District committees on Student activities, E. O. Osburn and F. C. Lindvall, have been added to the convention committee. J. H. Kelly, chairman of the subcommittee on publicity, is unable to serve and in his place R. E. Kistler has been appointed.

Fundamental Research in Electric Welding

The following self-explanatory item has been submitted by the Institute's committee on research:

"What can be done in the way of getting research investigators sufficiently interested to volunteer to take up research investigations is illustrated by the success of the efforts of the fundamental research committee of the American Bureau of Welding, with H. M. Hobart (A'94, F'12 and member for life) of the General Electric Company, chairman. As practically all of these projects have to do with electric welding, the research committee of the Institute feels that this accomplishment should be brought to the attention of the members of the Institute.

"A total of 87 projects have been initiated. Some of these are duplicates, that is, the same project is being worked on by more than one investigator but there are over 60 different subjects in the list. A total of 71 individuals are doing the work in 29 colleges and universities, and 11 industrial and Government laboratories. As all of this work is being done quite voluntarily without any financial support other than the negligible amount that may be involved in supplying weld specimens that are required. The majority of the men are busy professors and it is very much to their credit that they undertake these research projects "on the side." It is also evident that there is plenty of the research spirit in our technical schools which will respond to inspirational leadership.

"The Institute's committee on research

A Cornell Residential Hall to Be Used During the Summer Convention

BALCH Hall, one of a group of residential halls available for housing guests at the Institute's annual summer convention to be held this year on the campus of Cornell University, Ithaca, N. Y., June 24–28. The exterior of this hall is shown here, together with an interior view of one of the students' rooms.

has been advised that anyone interested in the details of this program can obtain a copy of a complete list of the projects, the men carrying them out, their affiliation, etc., together with any other details upon application to H. M. Hobart, chairman, fundamental research committee, American Bureau of Welding, Engineering Societies Building, 29 West 39th Street, New York, N. Y."

Suggestions for Section Activities

FOR the purpose of improving the quality of the meetings of the Institute's numerous Sections, and increasing the interest of members in them, the circulation of ideas among the Sections is desirable. I. Melville Stein, chairman of the A.I.E.E. Sections committee, has summarized the practices of a few of the Sections which depart somewhat from customary procedure, and for the benefit of other Sections, these items are presented herewith:

A Suggestion From Our Canadian District

Vice President A. H. Hull, of the Canadian District (number 10) recently called to the attention of the Sections in his District an additional Institute activity which might be undertaken by the Sections.

Specifically, Vice President Hull called attention to the interesting news items appearing in Electrical Engineering, such as "Message from the President," "Letters to the Editor," and other items appearing under "News of the Institute and Related Activities," and suggested that the membership could be kept better informed on such matters if important news items, such as these, were reviewed briefly at Section meetings. It was Vice President Hull's suggestion that the executive committees of the Sections appoint individuals to review such news items and to provide 10 minutes or so at each Section meeting for the reviewer or reviewers to present briefly the ideas contained in these news items.

Judging from the comments of the Sections' officers in District number 10, the suggestion was received enthusiastically and is being tried out in a number of the Canadian Sections. It is too early to report definite results, but the operation of this plan in the Canadian District will certainly be well worth watching.

It has been suggested that this same general idea might be successful in connection with strictly technical papers appearing in Electrical Engineering. Specifically, it has been suggested that the Section executive committees might appoint individuals known to be familiar with particular technical articles appearing in Electrical Engineering, to present, briefly, before Section meetings, the high-lights of these articles, so that those members not expert in a particular field could be kept informed in a general way.

Section Meeting Notices

There is a great diversity in the type of notices sent out by various Institute Sections. Many of these notices are in such excellent form that it is obvious that considerable time and thought have been given to their preparation. A discussion of all of the excellent forms used would be too lengthy to be included here.

The Cincinnati, Ohio, Section has recently adopted a form of notice, which, not only is excellent in form, but includes a distinct feature that deserves specific mention, that is, the inclusion on each meeting notice of a photograph of the speaker. The notice is arranged in a dignified form on standard $8^1/_2$ by 11 inch paper and reproduced from the original typing and the original photograph by the offset printing process.

Forum Meetings

The Toledo, Ohio, Section has adopted a form of meeting which it calls "forum meetings," to satisfy the desire of its members for meetings in which general current topics can be discussed. The forum meetings are additional to the regular technical meetings and are held on days which not only do not conflict with the regular Section meetings, but are sufficiently spaced from the regular meetings to avoid having the members choose between one or the other type of meeting rather than attending both. At the forum meetings, men of real ability are obtained for speakers, to assure that the topic under discussion is well presented.

The popularity of the forum meetings is attested by the fact that when they were discontinued for a time because of economic reasons, the Section received many requests for their continuance and they have been resumed during the current year.

15 Minute Talks

Another local activity being conducted by the Toledo Section is a series of 15 minute talks on fundamental electrical theory, one of these talks preceding each regular meeting of the Section. All the speakers for these 15 minute talks are chosen from the Section membership and experience with these meetings over a period of several years has shown to have the following advantages:

1. The bringing to light of latent local talent which otherwise might not have been revealed.
2. The re-establishment in the minds of the audience of certain phases of fundamental theory, which, because of lack of use, had almost been forgotten.
3. An increase in attendance at meetings.

At first the speakers were allowed to choose their own subjects for these 15 minute talks, but later the subjects of the talks were selected according to a program. In neither case was any attempt made to relate the subject of the 15 minute talk to the main subject of the evening.

Views of the Boulder Dam Project

Various phases of the Boulder Dam project on the Colorado River between Arizona and Nevada, and of the 275 kv transmission line connecting it with Los Angeles, Calif., are illustrated in these reproductions of 16 recently taken photographs. Photograph 1, showing Boulder Dam, was taken on March 20, 1935. Photographs 2 to 9, inclusive, showing other views of the Boulder Dam project, were taken on March 13; final height of the dam is shown, although the roadway across the top of the dam was not quite completed at that time. Photographs 10 to 16, inclusive, showing the transmission line, were taken on March 19. All were taken by D. M. Simmons, chairman of the Institute's committee on power transmission and distribution. The Boulder Dam project is being constructed by the U.S. Bureau of Reclamation, and that transmission line which is illustrated here is being erected by the Bureau of Power and Light of the City of Los Angeles.

(1) View of Boulder Dam and the intake towers, looking downstream

(2) Passenger launch on the lake being created above the dam

(3) Spillway on the Nevada side of the river

(4) Boulder Dam, looking upstream, and showing the Nevada wing of the power house

(5) View from Lookout Point, near the dam, showing the water forming some 6 miles upstream

(6) Top of Boulder Dam, intake towers, and the spillway on the Arizona side of the river

(7) The dam and a section of 30-foot penstock. To get the scale, note the people standing to the right of the penstock

(8) Downstream face of the dam, and the 2 wings of the power house; the Nevada wing is on the left, Arizona wing on the right

(9) Bottom of the excavation, showing the Arizona wing of the power house

(10) Connecting a dead end insulator string on a tower near Jean camp, about 70 miles west of Boulder Dam

(11) A dead end insulator string being raised to a tower at Jean camp

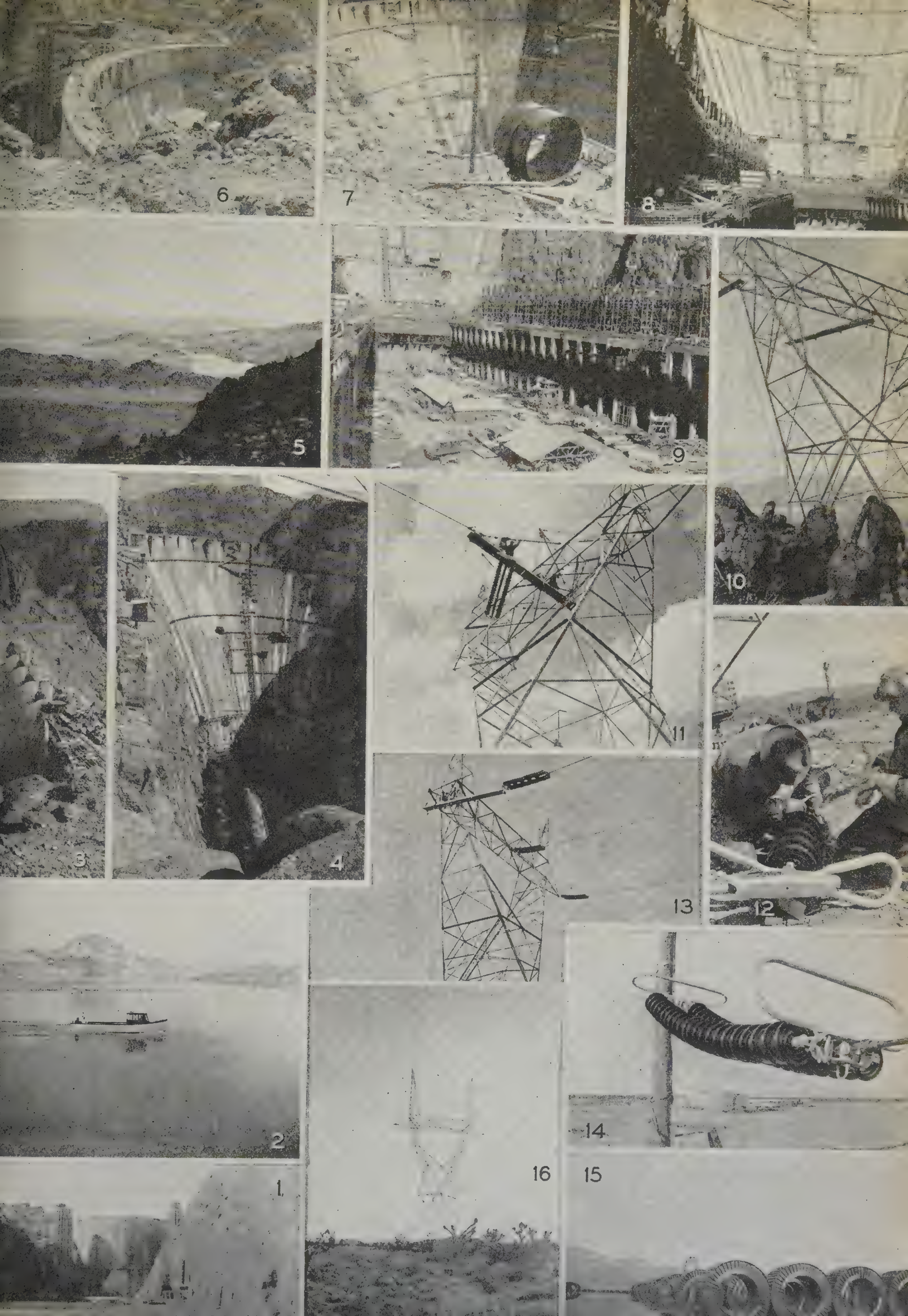
(12) Assembling a suspension insulator string near Kingston camp, about 40 miles west of Boulder Dam

(13) A dead end tower near Kingston camp; in this photograph and in numbers 10 and 11, note the men on the tower

(14) Dead end assembly at Jean camp for exhibition purposes; this assembly, including an I-beam for stiffening it during handling, weighs almost 700 pounds

(15) A supply of reels at Jean camp, each reel containing one mile of 1.4 inch diameter hollow copper cable for the transmission line. This conductor, and other features of the line, are described in a paper on pages 494–512 of this issue. (Among other papers discussing the line and dam project are 2 in the April 1935 issue and 2 scheduled for issues in the near future)

(16) A transposition tower east of Jean camp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E.C.P.D. Reports on Plans to Guide Students, Accredit Schools, and Promote Professional Status

DEVELOPMENTS in the co-operative program of engineering societies, educators, and representatives of state licensing boards looking toward the improvement of the engineering profession and the enhancement of the status of its members are recorded in the second annual report of the Engineers' Council for Professional Development, published on April 15, 1935.

The report, copies of which may be obtained at the headquarters of the E.C.P.D., secretary, 29 West 39th Street, New York, N. Y., is a pamphlet of 44 pages and includes 4 individual reports of the E.C.P.D.'s principal committees on student selection and guidance, engineering schools, professional training, and professional recognition.

Dr. C. F. Hirshfeld (A'05), director of research, Detroit (Mich.) Edison Company, and C. E. Davies, secretary, The American Society of Mechanical Engineers, acting, respectively, as chairman and secretary of the E.C.P.D. for 1934, call attention in the main report to the progress made during the year. The 7 participating bodies approved the recommendation that E.C.P.D. be established as an accrediting agency for schools of engineering. Two of the participating societies, the American Society of Civil Engineers, and The American Society of Mechanical Engineers, approved in principle a definition of an engineer, proposed by the E.C.P.D., and standard grades of membership in engineering societies, a recommendation of the E.C.P.D. Another participating body, the National Council of State Boards of Engineering Examiners, approved the definition.

Aided by a grant of $2,800 from the Engineering Foundation for publications and for the work being conducted in student selection and guidance, in post-college training and development, and in professional recognition, E.C.P.D. was able, during 1934, to supplement and extend the voluntary efforts of its numerous committee members. As a result, substantial progress is noted in the reports of the Council's 4 major committees.

R. L. Sackett, dean, college of engineering, Pennsylvania State College, in the report of the committee on student selection and guidance, of which he is chairman, says that during 1934 the committee concerned itself with 3 major problems:

1. The selection of a suitable booklet for informing high-school and secondary-school students about engineering.
2. Consideration of ways and means whereby this booklet could be used to the best advantage by students in secondary schools.
3. The development of some means whereby boys qualified to take up engineering could be selected from among those who apply for entrance to engineering schools.

The report describes 3 experiments in guidance conferences for secondary-school students.

Setting up a procedure by means of which the accrediting of schools of engineering may be undertaken by E.C.P.D. is described by Dr. Karl T. Compton (F'31), president, Massachusetts Institute of Technology, Cambridge, in the report of the committee on engineering schools, of which he is chairman. Supplementing the report is the complete questionnaire to be used by the committee in securing the basic facts with respect to the engineering school seeking to be accredited by E.C.P.D.

For the year's activities of the committee on professional training, its chairman, Gen. Robert I. Rees, assistant vice president, American Telephone and Telegraph Company, New York, N. Y., reports a comprehensive method by which junior engineers may make a personal appraisal of themselves. Searching questions to be answered by the individual cover his occupation and his personal and professional status and provide the basis of formulating a general and an immediate program for his own development. Another accomplishment of the committee is the revision of an annotated reading list of more than 100 carefully selected books covering a broad range of nonengineering subjects. Sections of this list are being published month-by-month in current issues of ELECTRICAL ENGINEERING.

Two major efforts of the committee on professional recognition, whose chairman is Conrad N. Lauer, president, Philadelphia Gas Works, Philadelphia, Pa., were devoted to the adoption of a tentative draft of a program of certification into the engineering profession, and the explanation of the committee's proposed definition of the term "engineer" and of its suggested standard grades of membership in engineering societies. The committee's program of certification into the profession is given in detail.

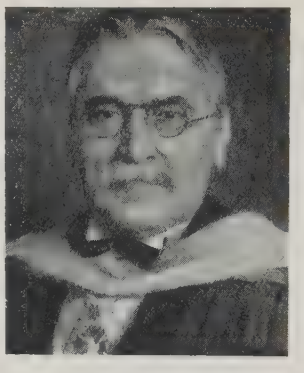
In addition to the reports of the 4 major committees, the main report also includes the charter and rules of procedure of E.C.P.D., the verbatim statement of 5 policies previously adopted by E.C.P.D., and the complete personnel of the Council and all of its committees. The report is thus a complete and authoritative source of information on the work and organization of this body.

The Engineers Council for Professional Development is a conference of engineering bodies organized to enhance the professional status of the engineer through the co-operative support of the national organizations directly representing the professional,

In Memoriam

DR. Michael Idvorsky Pupin, an Honorary Member of the Institute, and its thirty-eighth President, died on March 12, 1935, in his seventy-seventh year.

Coming to the United States alone at the age of 15, he devoted all possible time to studies while earning his living at various types of work. His unusual ability and his determination to secure a good education enabled him to enter Columbia University in 1879 and to graduate in 1883. After pursuing advanced study in mathematics and physics at the University of Cambridge and in thermodynamics at the University of Berlin, he received the degree of doctor of philosophy from the latter in 1889.



MICHAEL I. PUPIN

Upon returning to the United States, he became a member of the faculty of Columbia University, entering upon a long career which was to bring him world-wide fame as educator, scientist, engineer, inventor, and author, and many high honors from governments, universities, and scientific bodies.

Gifted with a thorough understanding of human nature, he ever stood firmly in opposition to those who tried to create a breach in the relations of science and religion.

Doctor Pupin joined the Institute in 1890, was transferred to the grade of Fellow in 1915, and was elected an Honorary Member in 1928. He served on various committees, as director 1892–95, as vice president 1895–97 and 1901–03, and as president 1925–26. He received the Edison Medal in 1920, the Washington Award in 1928, the John Fritz Medal in 1932, and other medals.

BE IT THEREFORE RESOLVED: That, upon behalf of the membership of the American Institute of Electrical Engineers, the executive committee hereby expresses its sincere regret at the death of Doctor Pupin and its appreciation of the important contributions he made to the development of the Institute and of the fields of engineering and science; and be it further

RESOLVED: That these resolutions be entered in the minutes and transmitted to the members of Doctor Pupin's family.

—A.I.E.E. Executive Committee, March 29, 1935

technical, educational, and legislative phases of an engineer's life. The participating bodies are: American Society of Civil Engineers, American Institute of Mining and Metallurgical Engineers, The American Society of Mechanical Engineers, American Institute of Electrical Engineers, Society for the Promotion of Engineering Education, American Institute of Chemical Engineers, and National Council of State Boards of Engineering Examiners.

The executive committee is composed of C. F. Hirshfeld (A'05), *chairman*, J. Vipond Davies, F. M. Becket, W. E. Wickenden (A'07, M'13), C. F. Scott (A'92, M'93, F'25, HM'29, member for life, and past-president), H. C. Parmelee, R. I. Rees,

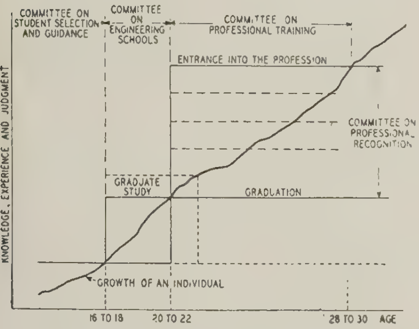


Chart illustrating the fields of activity of the 4 committees of the Engineers Council for Professional Development

D. B. Steinman, and the secretary is George T. Seabury, 29 West 39th Street, New York, N. Y. A list of the officers, representatives, and committee members of E.C.P.D. was given in Electrical Engineering for February 1935, pages 249–50.

The activities of the 4 major committees are organized to cover the educational and professional needs of the engineer from the time he is a student in the secondary school, faced with the problem of entering upon a college education leading to a professional career, to the time he has developed in the practice of his chosen branch of the engineering profession to such an extent that he is eligible for membership in one of the professional engineering societies and for registration for license to practice engineering under the laws of his state. The accompanying diagram indicates the areas of influence in the engineer's life to which the activities of these 4 committees are related.

Other articles on the activities of E.C.P.D. are given in the 3 preceding issues of Electrical Engineering.

A Reading List for Junior Engineers

A LIST of books recommended for reading by junior engineers has been prepared by a number of eminent men, many of them distinguished in the engineering profession. Previous sections of this list have been published in Electrical Engineering for December 1934, page 1667, January 1935, page 133, March 1935, page 345, and April 1935, page 456. Two additional sections are published herewith, and others are scheduled to follow in subsequent issues. The complete list includes more than 100 titles.

Systematic reading of worth while books adds breadth and vision to the background of an engineer and should be considered a part of the intellectual development designed to fit the young engineer for full professional recognition. It is suggested that over a period of about 4 years a minimum of about 25 of these books might be selected and read, with the limiting recommendation that the selection made will include at least one book in each classification, preferably in accord with the individual engineer's most vital interests.

Biography and Travel

Abraham Lincoln, Lord Godfrey Charnwood. Henry Holt, 1916.

Two Years Before the Mast, R. H. Dana. Macmillan, 1923.

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Alexander Graham Bell, C. D. Mackenzie. Houghton, Mifflin, 1928.

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Life of George Westinghouse, Henry G. Prout. Scribner, 1922.

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Fine Arts

Scope of Music, Percy Buck. Oxford University Press, 1924. A series of 10 lectures on physics of sound, origin and place of music as an art, the nature of beauty, melody, form, and psychology of music.

Simple Guide to Pictures and Painting, M. H. Bulley. Dutton, 1928. Deals with principles of construction—design, personality, craft, tradition and ways in which a painter works. Outlines the development of painting from Byzantine to modern French.

Art Through the Ages, Helen Gardner. Harcourt, Brace, 1926. World survey of history of art—architecture, painting, sculpture, and the minor arts from earliest times to the present.

Enjoyment of Architecture, T. F. Hamlin. Scribner, 1921. Fine explanations for laymen of basic principles of architectural design and construction, ancient and modern structures, with special attention to American buildings.

Theatre, edited by E. J. R. Isaacs. Little, Brown, 1927. A collection of 30 essays on the art of the theatre.

Listening to Music, Douglas Moore. W. W. Norton, 1932. Analysis, interpretation, and appreciation through intelligent listening. No previous training in music required.

Photoprints Service Available From Engineering Library

The Service Bureau of the Engineering Societies Library has supplied almost 200,000 photoprints of material in the library to individual engineers, engineering corporations, and libraries throughout the world, in a 5 year period. This service makes it possible for an engineer, who is far from library service or whose local library cannot provide the great wealth of engineering information housed in the Engineering Societies Library, to obtain copies of articles or of books that he needs in his work.

By this method is it possible for the service bureau to supply exact copies of printed or manuscript data, graphs, charts, maps, and illustrations at a minimum cost. Pages may be photographed just as they appear in the book, or, in the case of small print, they may be enlarged for increased clarity and ease in reading.

Photostats are sent either in negative (with white print on a black background) or in positive form (with black print on a white background). However, the cost of the positive print is double that of the negative print because a negative print must be made first.

Photoprinting, as well as searching, abstracting, preparation of bibliographies and translations, and all other work of the service bureau is done at cost. For further information or quotations, write, telephone, or telegraph the Engineering Societies Library, 29 West 39th Street, New York, N. Y.

(Articles on other services available from the Engineering Societies Library were given in Electrical Engineering for December 1934, pages 1668–9, January 1935, pages 130–1, and March 1935, page 341.)

Physical Society Meetings. The summer meeting on the Pacific Coast of the American Physical Society will be held in affiliation with the Pacific division of the American Association for the Advancement of Science in Los Angeles, Calif., during the week of June 24–28, 1935; it is planned to hold one session at California Institute of Technology, Pasadena. Another meeting of the American Physical Society will be held in Minneapolis, Minn., June 21–22, 1935.

E.E.I. to Meet in Washington. The third annual convention of the Edison Electric Institute will be held at The Mayflower Hotel, Washington, D. C., June 3–6, 1935. Subjects to be discussed are: building good will, rural electrification, government in business, rates, and sales programs.

"Scientific Education—What Is Wrong With It?"

A highly informative meeting at which many critical and original ideas were expressed regarding the education of engineers and scientists, was sponsored by the New York Electrical Society, Inc., and held Wednesday evening, March 27, 1935, in the auditorium of the Engineering Societies Building, New York, N. Y. This "Science Forum" had for its subject "Scientific Education—What Is Wrong With It?"

The speakers who addressed the audience were Dr. William E. Wickenden (A'07, M'13) president of Case School of Applied Science, Cleveland, Ohio; Dr. Colin G. Fink, head of the electrochemistry department of Columbia University, New York, N. Y.; Dr. Alan Gregg, director of medical sciences for the Rockefeller Foundation, New York, N. Y.; and Dr. Harry Woodburn Chase, chancellor of New York University, New York, N. Y. Discussion from the floor was led by Gano Dunn (A'99, M'94, F'13, and Life Member) president, J. G. White Engineering Corporation, New York, N. Y., and past president of the Institute as well as of the New York Electrical Society; J. W. Barker (M'26, F'30) dean of engineering, Columbia University, New York, N. Y.; Dr. Frank L. Babbott, Jr., president, Long Island (N. Y.) College of Medicine; H. C. Rentschler, director of research, Westinghouse Lamp Company, Bloomfield, N. J.; Dr. E. E. Free, consulting engineer, New York, N. Y.; and Gen. R. I. Rees, assistant vice president, American Telephone and Telegraph Company, New York, N. Y.

Doctor Wickenden's address, being particularly pertinent to the education of electrical engineers, is presented in full in this issue of ELECTRICAL ENGINEERING, pages 471–3.

Doctor Fink, in his address, spoke primarily in terms of high school graduates, and complained that natural sciences today are in general taught to children in primary and secondary schools "in a manner so uninteresting that it tends to destroy for life an interest in science." In urging the importance in modern life of an understanding of the basic principles of the fundamental sciences he said "it might be argued that not every child needs to be acquainted with scientific matters, but such argument would hold true only perhaps 50 years ago. It certainly does not apply today. Every high school graduate today, whether he goes to college later or not, should be trained in the most essential principles of the various sciences, notably biology, chemistry, and physics. Today it is just as important to be schooled in the sciences as it was formerly to be schooled in the '3 R's.' A knowledge of the properties of the gas in the kitchen oven, or the gasoline in the automobile, or of the composition of the basic foods, is more important to high school graduates today than is a knowledge of the dates of the wars of Napoleon, the ability to compose poetry, or to recite Vergil." Doctor Fink recommended that science should be taught in the high schools more through the laboratory and less through the library and blackboard; that the best teachers available in science should be employed in the high schools; and that the ground covered be reduced rather than increased, so that the basic principles may be brought home in such a way as to arouse the interest of the child in matters scientific, and to encourage the development of such interest.

Doctor Gregg spoke of educational procedures in terms of the distinction between tactics and strategy, stating his belief that education at present is too largely tactical and that entirely too little attention is given to strategy. He defined tactics as the ability to use one's forces to meet conditions already decided upon, or outlined, and strategy as the vital art of choosing the circumstances under which one's known strength or ability could be developed or applied to the best advantage. He deplored overemphasis of systemized routine curricula except perhaps as groundwork, pleading for a more general realization that when a mature student has "finished the business of giving proof that he is competent in assigned tasks he should be given a wider freedom and a more generalized responsibility and experience in choosing his own field of work." In this connection he criticized particularly such practices as the assignment of thesis subjects. With particular reference to the pursuit of the fundamental research that is essential to scientific advancement, Doctor Gregg emphasized the great importance of liberal and long-term fellowships that would provide for terms of research ranging from 2 to 10 years or more according to requirements, instead of the present tendency to provide one year fellowships which unduly restrict the extent of the work that can be carried on.

Editor Appointed by A.S.C.E

Beginning with the May 1935 issue the editorial work for *Civil Engineering*, monthly publication of the American Society of Civil Engineers, is in charge of P. H. Carlin, an associate member of that society. Mr. Carlin succeeds Walter E. Jessup, who, as announced in ELECTRICAL ENGINEERING for April 1935, page 455, has been appointed field secretary of the society.

To his new work Mr. Carlin brings excellent technical training, considerable engineering experience, and a knowledge of society affairs and editorial practice. A native of Philadelphia, Pa., he is a graduate of the University of Pennsylvania with the degrees of bachelor of science in civil engineering in 1922, and civil engineer in 1930, has studied law at Temple University, and is a registered professional engineer in Pennsylvania.

Much of his experience has been with the Philadelphia Department of City Transit, where he was engaged from 1924 through 1932 on the design of subways and in writing specifications for subways and their appurtenances. He has also filled a number of shorter engagements in building and highway design and construction. Following his work on Philadelphia subways, Mr. Carlin was for some time with C. E. Myers, consulting engineer, Philadelphia. His latest engagement before taking up the duties of editor of *Civil Engineering* was with the

Near the Scene of a Future A.I.E.E. Convention

THE beautiful setting of Paradise Inn at Paradise Valley with Mount Rainier in the background towering 14,408 feet above sea level. This point is a 2 hour drive from Seattle, where the 1935 Pacific Coast convention of the Institute will be held August 27–30. Excellent highways lead from Seattle to this famous playground in Rainier National Park.

Pennsylvania State Emergency Relief Board as assistant director, Luzerne County Work Division, with headquarters at Wilkes-Barre.

He has for some time been active in the society's Philadelphia section, having been since 1931 editor of that section's monthly publication, *The News*, which he has expanded into an attractive 8 page form.

"Science Series" Reprint Demand Exceeds Supply

An expression of regret is offered to the many Institute members who entered orders for the "Science Series" reprint too late to be filled. In an effort to guard against just such an eventuality, the notices published in the November and December 1934 issues of ELECTRICAL ENGINEERING urged all interested members to file advance orders not later than January 7, 1935, the date on which the reprint was scheduled to go to press. By that date, orders for some 600 copies had been received by the editorial department. As a safety factor, and in an attempt to anticipate late orders, this amount was increased by more than 60 per cent, and some 1,022 copies of the reprint were issued, after which the type was killed in accordance with established procedure.

In addition to the flood of orders that came in from members in the United States and Canada, orders were received from members in 18 foreign countries throughout the world. This widespread popular demand for reprints of the 13 special articles that appeared last year in ELECTRICAL ENGINEERING in itself constitutes a fitting testimonial of appreciation for the generous contributions of the several authors, and for the hard work underlying the project that was put in by Dean Robert E. Doherty of Yale University, during his term as chairman of A.I.E.E. committee on education (1932–33), and by those who assisted him in organizing and developing the project. Unfortunately, the reprint is out of stock, but the articles themselves are still available to those members who have kept their issues of ELECTRICAL ENGINEERING.

International Congress for Scientific Management. The International Congress for Scientific Management will be held in London, Eng., July 15–20, 1935. An attendance of about 2,000 is expected. There will be an official reception by the British government, and the Court of Common Council of the City of London will extend to delegates an invitation to an evening reception in the Guildhall. Several other official social functions are being organized.

A.S.T.M. to Meet in Detroit. The 38th annual meeting of the American Society for Testing Materials will be held in the Book-Cadillac Hotel, Detroit, Mich., June 24–28, 1935. An interesting technical program covering a large number of subjects has been arranged. Also, the society's third exhibit of testing apparatus will be open throughout the 5 days of the meeting. Exhibits of leading companies interested in testing apparatus and related equipment fields, and of several of the society's committees, will be presented.

Engineering Foundation

Notes on Activities Since January 1, 1935

Results of the election held by The Engineering Foundation at its annual meeting February 21, 1935, and a summary of the annual report of The Engineering Foundation for 1934, were presented in ELECTRICAL ENGINEERING for April 1935, pages 457–9. Supplementing this information, the following brief item on activities of Engineering Foundation since January 1, 1935, may be of interest. As pointed out in the previous issue, The Engineering Foundation is a department of United Engineering Trustees, Inc., joint agency of the 4 national societies representing the civil, mining and metallurgical, mechanical, and electrical engineers, and its present preferred activity is research.

On January 2, 1935, research on the plasticity of metal was begun under the leadership of Dr. A. Nadai, an international authority, in co-operation with the University of Pittsburgh and a number of industrial companies.

Through provision of a special contribution, a research associate engaged in barodynamic research was added on February 4 to Professor Bucky's staff at Columbia University. Appreciation of members of the mining profession in this work has been expressed. A clear picture of the action of mine roofs and of the proper placement of roof supports has been afforded by this work.

"Principles of Phase Diagrams," the fifth book in the series on alloys of iron, was issued in March 1935. It explains and illustrates the thermodynamic principles underlying the behavior of a system of metals or other substances under changing conditions of temperature, composition, and pressure. It is a tool book for metallurgists in industry and a textbook for colleges.

Progress has been made by a planning committee toward stating a co-ordinated, comprehensive project in welding research, arranging a conference of representatives of interested organizations and industries, and selecting men to be nominated for members of the proposed welding research committee. Members of the planning committee are: F. M. Farmer (A'02, M'12, F'13) *chairman*, chairman of the A.I.E.E. research committee; Dr. D. S. Jacobus (A'03) president, American Welding Society; and Prof. C. A. Adams (A'94, M'05, F'13) director, American Bureau of Welding.

Appointment of a welding research committee was authorized, if a plan for coordinated welding research and nominations for members be received from the A.I.E.E. and associated organizations. Other committee changes included the reappointment of the research procedure committee, D. Robert Yarnall, *chairman*, and the iron alloys committtee, George B. Waterhouse, *chairman*. A platform and program committee, Otis V. Hovey, *chairman*, was appointed. The education research committee, Harvey N. Davis, *chairman*, was discharged, with special appreciation for producing the booklet "Engineering: A Career—A Culture," and for other valuable services.

The annual report of The Engineering Foundation for 1934 (summarized in the April issue of ELECTRICAL ENGINEERING) was ordered printed.

American Engineering Council

The Federal Work-Relief Bill

American Engineering Council, as the agency of its sponsor societies and allied groups, is actively negotiating in Washington with regard to the engineers' part in the vast program of the $4,880,000,000 work-relief bill which gives to the president all of the money and most of the power he first asked.

The following excerpts from Council's recent news letter tell some of the story regarding this bill:

To engineers, this measure brings deep responsibilities, for without engineering technique, such a program could neither be planned nor executed. It brings complex problems of professional status and of adjustment to new lines of activity. But most of all, the program brings hope to thousands of engineers now losing their skill in idleness or in makeshift jobs.

The engineering nature of the program becomes evident from the type of projects earmarked in the bill. The $4,880,000,000 represents an appropriation of $4 billion plus the release of approximately $880 million from past appropriations. The latter sum is mainly for continuance of relief through June 30 and for repayment of P.W.A. funds temporarily used for relief while passage of the bill hung fire. Allocation of the $4 billion follows:

Highways; roads; grade crossings	$800 million
Rural rehabilitation and relief in stricken areas; water conservation; trans-mountain water diversion; irrigation; reclamation	500 million
Rural electrification	100 million
Housing	450 million
Assistance for educational, professional, and clerical persons	300 million
Civilian conservation corps	600 million
Loans and grants to states, municipalities, etc., not less than 25 per cent of each loan or grant for work	900 million
Sanitation; prevention of soil erosion; prevention of stream pollution; sea coast erosion; reforestation; flood control; rivers and harbors; miscellaneous	350 million
Total	$4,000 million

Not to exceed 20 per cent of the $4 billion

may be used to increase any one or more of the above items. This listing may be somewhat misleading in that it represents classes of work rather than functional divisions of the program. Any given item may be split between several operating agencies of the government.

Assistant Secretary Appointed by A.E.C.

L. V. Reese, who has been handling rural industrial communities in the rural rehabilitation program of the Federal Emergency Relief Administration resigned April 1, 1935 to become assistant secretary of the American Engineering Council in Washington, D. C. He has also served the F.E.R.A. as executive secretary of the District of Columbia Rehabilitation Corporation and as planning engineer for the Texas Relief Commission.

In his new position, Mr. Reese will assist the executive secretary, Frederick M. Feiker, in carrying out the enlarged program of the American Engineering Council voted at its recent annual meeting as a service agency for relating the organized engineering professions to national affairs in the public interest.

He will serve also as a liaison officer between the federal agencies and organized national, state, and local professional engineering societies, by which 222 localities are co-ordinated.

His assistance will be available both to government agencies and to the member organizations of A.E.C., to make effective the engineers' contribution in planning and executing the $4,880,000,000 work-relief program, almost every phase of which is an engineering job.

L. V. Reese

Mr. Reese, who is 43, was educated in civil engineering at the University of Texas, and in mechanical, metallurgical, and industrial engineering at Columbia and New York Universities. His experience in engineering and executive capacities has been extensive. Prior to his service with federal agencies, he was engaged in the industrial, public utility, and construction fields. He was assistant to the president and manager of the research division of the American Laundry Machinery Company, vice president and general manager of the Erie City Iron Works and chief engineering executive of the American Metal Company and the United States Metals Refining Company. During the War, he was assistant supervising constructing quartermaster on cantonment work for the U.S. Army. For several years before the War, he managed his own engineering business, doing civil and industrial engineering and the construction of industrial plants, public buildings, and utilities. Along with his other experience, Mr. Reese has kept himself up to date on agricultural life through the side-line operation of farms and ranches.

Other Activities of A.E.C.

Other items taken from American Engineering Council's recent news letter reflecting activities of Council follow:

The new plan of organization for Council's regular and standing committees for 1935 has been completed. The report, which outlines the functions of each committee and lists the personnel, is available upon request. It is being mailed to member organizations and to committee members.

Council membership is gaining under the new plan of nominal dues for state and local societies, and several such societies have made definite application for membership within the last month.

The patent committee of A.E.C. has declared a general opposition to the Sirovich bill for regulation of patent pools and agreements.

Rural electrification plans were advanced by a delegation from the American Society of Agricultural Engineers, in Washington recently. The group headed by Dr. Glen W. McCuen, president of the A.S.A.E., called upon Doctor Tugwell and other prominent officials who will be influential in the rural work. They offered the services of A.S.A.E. to help the program in a constructive way.

Letters to the Editor

CONTRIBUTIONS to these columns are invited from Institute members and subscribers. They should be concise and may deal with technical papers, articles published in previous issues, or other subjects of some general interest and professional importance. ELECTRICAL ENGINEERING will endeavor to publish as many letters as possible, but of necessity reserves the right to publish them in whole or in part, or to reject them entirely.

STATEMENTS in these letters are expressly understood to be made by the writers; publication here in no wise constitutes endorsement or recognition by the American Institute of Electrical Engineers.

Measurement of Quadrature Axis Synchronous Reactance

To the Editor:

The following simple test for experimentally determining the quadrature axis synchronous reactance of a salient pole synchronous machine may be of interest to your readers. It can be applied in cases where the well-known slip test cannot be performed satisfactorily—for example, in testing a synchronous machine which is not coupled to a prime mover by means of which the slip can be adjusted to a small value. In such cases, if it is attempted to perform the slip test by operating the synchronous machine as an induction motor, it will frequently be found that it is impossible to operate at a small slip without having the machine pull into synchronism and run as a reluctance motor.

Operate the machine at no load as a reluctance motor, the power supply being from a generator whose voltage can be varied and which is sufficiently large compared with the machine being tested so that the power source can be considered as an infinite bus. Gradually reduce the terminal voltage until the machine falls out of step, observing as carefully as possible the no-load power input and terminal voltage at which loss of synchronism occurs. From these readings, the quadrature axis synchronous reactance can be calculated as follows:

As is well known, the power input P to a salient pole synchronous motor of negligible resistance operating from an infinite bus can be expressed as

$$P = \frac{EV}{x_d}\sin\delta + \frac{V^2(x_d - x_q)}{2x_dx_q}\sin 2\delta \qquad (1)$$

where

E = excitation voltage
V = terminal voltage
x_d = direct axis synchronous reactance
x_q = quadrature axis synchronous reactance
δ = load angle of the machine (angle between E and V)

If operated as a reluctance motor, $E = 0$, and hence

$$P = \frac{V^2(x_d - x_q)}{2x_dx_q}\sin 2\delta \qquad (2)$$

If the machine is operated at no load and reduced voltage, P is practically equal to the friction and windage loss. As V is reduced, as in the test described above, δ will increase until pull-out as a reluctance motor occurs when

$$P = \frac{V^2(x_d - x_q)}{2x_dx_q} \qquad (3)$$

The values of P and V at pull-out can be determined as in the above test. The direct axis synchronous reactance x_d can be determined by well-known methods. Hence x_q is the only unknown in equation 3. Therefore from equation 3

$$x_q = \frac{V^2x_d}{V^2 + 2Px_d} \qquad (4)$$

Pull-out will usually occur at a terminal voltage of approximately 0.25 per unit (25 per cent). Hence the magnetic circuit of the machine will not be saturated. The unsaturated value of x_d should be used in

equation 4 and the value of x_q obtained will be the unsaturated value.

If the resistance r of the machine is approximately taken into account, it can be shown that

$$x_q = \frac{V^2(x_d + 2r)}{V^2 + 2Px_d} \qquad (5)$$

There are several possible modifications of the above simple test. For example, from equation 2

$$x_q = \frac{V^2 x_d \sin 2\delta}{V^2 \sin 2\delta + 2Px_d} \qquad (6)$$

If resistance is approximately taken into account, it can be shown that

$$x_q = \frac{V^2(x_d \sin 2\delta + 2r)}{V^2 \sin 2\delta + 2Px_d} \qquad (7)$$

If a stroboscope or other means of measuring the load angle is available, any simultaneous readings of P, V, and δ taken with the machine operating as a reluctance motor can be substituted in equations 6 or 7 and the corresponding value of x_q obtained.

Very truly yours,

CHARLES KINGSLEY, JR. (A'30)
(Instructor, Mass. Institute of Technology, Cambridge)

The Engineer's Influence on Public Opinion

To the Editor:

Allow me to make somewhat of an answer to a question in B. D. Willis' "Letter to the Editor" on "New Use for Overproduced Products." (See ELECTRICAL ENGINEERING, January 1935, page 136.)

Referring to the symposium talks of Dr. Virgil Jordan and Col. W. T. Chevalier, (ELECTRICAL ENGINEERING, November 1934, pages 1546–51), and to the fact that the national administration has complained of criticism without accompanying helpful suggestions, Mr. Willis does then make several common-sense and constructive plans. He finally asked, "Why is it not practical to discover the full value of our surplus stocks and consume them?"

One reason "why not" can be handled rather summarily. Politics (the U. S. A. sort) could regard such a program with indifference only. Not only are the necessary steps dispassionate and impersonal; worse, they do not lend themselves to indiscriminate placement of faithful party workers.

Another reason, having a philosophical tinge, leads a bit farther afield. Mr. Willis' suggestions have no "success" appeal. They are not spectacular, but common-sense. Actually, they are scientific. And, the attitude of the layman toward science is one of "uncritical credulity," yielded only on account of the successes of science. "Owing to its success, the scientific method has obtained immense prestige in the eyes of the layman. In spite of its prestige, however, the scientific method still remains very unpopular. The patient accumulation of all relevant evidence, the cautious framing of hypotheses, and the careful verification of them are almost unknown in ordinary human pursuits—such as politics, for example. And any attempt to apply such methods is strongly resented."—from "Science and the Layman," by J. W. N. Sullivan, *Atlantic Monthly*, September 1934.

Please note: "owing to its success. . ." Colonel Chevalier also spoke of the prestige gathered by success—the success of the American system that got along fine for 150 years. But, having a scientific viewpoint, he had to give opportunism its deserts: "We have been able to make the old speculative thing work because every time we cleaned out one bunch of suckers there was a new place for them to go and dig up some more for the wise ones to take away from then on the next turn-over."

Thus it is we come a bit closer to fundamentals.

Everitt Dean Martin claims most people look on "liberty" as freedom to get rich. It was Henry Ward Beecher who urged people to get rich as a most worthy human endeavor. But it was a Roman emperor, we are told, who put it more succinctly: "*pecunia non olet.*"

What Colonel Chevalier dubs "the old speculative thing," is a vital component of the stimuli of public opinion. Human mental activity is largely wishful thinking, along the lines of personal vindication and aggrandisement. Its intellectual level is about that of the Alger books. Having had a frontier and prodigious reserves of natural resources, *ergo* and *of necessity*, it must yet be so. People, in the mass, seem unable to grasp the fact of there having to be more victims than racketeers, more betters than bookmakers, more lambs than either bulls or bears. They believe, implicitly, that "Every man a King" is perfectly possible.

Human nature, being what it is, has always believed, and still does, that "deals" are a more practical, a sounder, a more sensible basis of action than ideals. The leaders of the early United States—sometimes known as "the funding fathers"—subscribed pretty generally to this creed. The Credit Mobilier episodes of Grant's administration demonstrated it to be a lively principle 100 years later. The Teapot Dome activities of Harding's day showed it but waiting an opportunity to express itself again.

In brief, I have but tediously piled Ossa upon Pelion to indicate that public opinion and political expediency are instinctively against such common-sense proposals as are outlined by Mr. Willis.

Then, what to do? Some change must be accomplished in public opinion, if not in human nature. But how to accomplish it?

Manifestly, it will have to come through those the public accepts as mentors. On this principle, one suggestion I have seen is that newspapers, in reporting anti-social occurrences, refrain from adjectives and style that lend "glamour" to the events and participants. To do, rather, significant journalism, than to write sensational claptrap.

Another scheme is based on the motives which determine buying habits. Study has shown the character traits most useful in promoting large-scale purchasing are snobbishness, desires for adequacy, desires for vicarious romance, etc. Some overhauling to advertising methods would therefore seem helpful. Especially so, if the emphasis of appeal be shifted away from the more paltry emotions.

It can thus be deduced that engineers, in any scientific capacity, have no great opportunities here, no more than have medical men. Of the several professions, each acting in its professional capacity, clerics and legal persons would be of greatest aid. About all engineers can do is to convince themselves of the inapplicability of reason and scientific method to an emotional public sentiment. Then, *as ordinary citizens*, exert persuasion or pressure on those having influence to change their philosophy.

When, and if, the influential act on principle rather than in accord with policy toward constituents, congregations, clients —i. e., toward the "public" in any of its private and organizational manifestations—then, after a time, the methods of science may become applicable.

Very truly yours,

J. ANDREW DOUGLAS (A'18, M'29)
(Fairhope, Ala.)

Constant-Current A-C Transmission

To the Editor:

The presentation before the A.I.E.E. 1935 winter convention of the paper on "Constant Current D-C Transmission" by Willis Bedford and Elder (see ELECTRICAL ENGINEERING for Jan. 1935, pages 102–8) has introduced a most significant factor into the discussion of extra long distance transmission. It further has prompted the writer to here call the attention of the members of the Institute to the favorable possibilities of the use of constant alternating current in important transmission, a subject studied carefully by him some years ago.

This introduction of the constant current feature into the long distance d-c transmission system, adds a number of new and fundamental factors vitally affecting costs, efficiencies, and operability—sometimes favorably, sometimes not so favorably. The unique and to most engineers unfamiliar behavior of the current-potential conversion unit, in which equalized reactors and capacitors are similarly connected, so as to be in series in one circuit and in parallel in another, causes a profound modification of the natural performance of the system.

As appears in the paper, the characteristics of these conversion units depend upon the correspondence of the current in one circuit with the voltage in the other.

If equalized reactors and capacitors be connected in series across the primaries of the step up transformers of a typical existing 3-phase transmission system and the 3 constant-potential supply phases be applied between the mid points of these windings and the junction points between the reactors and the capacitors (see figure 1), a constant current will flow in the secondaries of the transformers and into the line. If similar and similarly connected reactors and capacitors be introduced in circuit with the secondary windings of the step down transformers, whose primaries are supplied with constant current, 3-phase constant-potentials will be produced between the mid points of the secondary windings and the junction points between the reactors and the capacitors, these being available for supplying the local

load. The connections, applicable to either end, are shown in the figure.

In this system, with the ideal circuit, free of all losses, the line *current* bears a definite ratio to the constant supply and delivery *potentials*, a ratio equal to the value of the equalized reactances or capacitances, and the *potentials* of the line bears the inverse ratio to the *currents* in the load and the generator, the current in the one circuit and the voltage in the other retaining a constant phase relation.

In such a system the generation of power is normal constant potential, the line transmission is constant current, and the delivery at the receiving end is normal constant-potential. In the ideal circuit no limitations to operation or load control are so introduced. The system as a whole, however, has certain striking inherent characteristics which may be briefly pointed out as follows:

1. In case of an overload on the receiving circuit an increase in potential in the line results, with the corresponding increase of line load transmitting capacity, this increase strengthening the tendency to hold synchronism. This behavior is in contrast to that of the constant potential line, in which an increase in load tends to drop the potential on the line and reduce its capacity and produce instability.

In favorable cases the adoption of this system will greatly increase the dependable capacity of existing lines. Provision must be made against too high a rise of line potential in the case of heavy overloads. There are several methods of accomplishing this result.

2. The lagging component of the load in the receiving circuit, as pointed out in the paper, becomes a leading component in the constant current line circuit giving more favorable line conditions. That is, the line instead of carrying a lagging current, has a leading current. The importance of this change from lagging to leading in its effect on the ability of the line to carry heavy loads is exceedingly important, as will be seen by comparing the line performance at 90 per cent or 95 per cent lagging load with that at 90 per cent or 95 per cent leading. The net result is a very great gain in the maximum stable load of a line. In this case the reactance of the line is operating to increase the line load capacity—and to this extent gives advantage over d-c transmission, in that the natural ohmic drop may thus be overcome in favorable designs.

On the other hand any variation of current strength along the line will tend to disturb the constancy of the potential at the receiving network, the line current being held automatically constant at the sending end. Some benefit may be secured in controlling the effect of such variation by synchronous condensers controlling the power factor at the receiving end and this may be made automatic. These matters become very complicated in considering the detail in any particular case. It should be noted that out-of-phase current components existing in the constant current line change sign in the constant potential generator circuit, but little importance attaches to this.

3. With the constant line current set up, the maximum energy to be handled by high voltage circuit breakers, when due to trouble on the high voltage circuits, is greatly reduced, and lower cost, quicker acting units

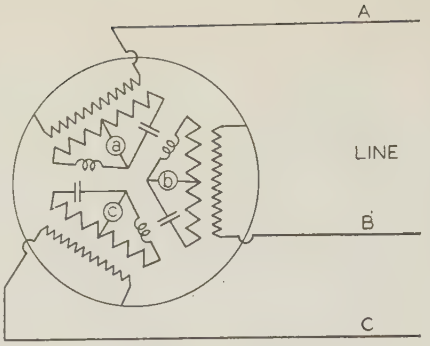

Fig. 1. Current-potential conversion unit

may be used. This is a matter of no small moment.

From another point of view it may be urged that no circuit breakers would be needed on the constant current circuit as such a current should not be interrupted. This is a matter to be considered in the light of circumstance existing in particular cases.

Further, the current interrupting duty on the lightning arresters is greatly reduced and either lower priced or more complete protection may be secured as a result. This feature may be compared to the ease of current interruption of ground faults in the constant current d-c line with the inverter operating in the reverse direction, as described in the paper.

Obviously a new system of relays is required.

4. The use of a constant line current means a constant line energy loss, equal to the full load loss, even at very light loads. While this may be unimportant for base load service, it would be prohibitive for emergency service. However, it is entirely possible to reduce this loss greatly in a polyphase transmission by using a lesser value of line current for the lighter loads, this calling for higher line potential for that condition. The change from one line current to the other may be made in a few minutes by making the change, leg by leg. The single line wire may be cut off at both ends—the phase transformers then de-energized and the low voltage taps changed and the load then resumed in that leg.

While the line resistance loss tends to remain constant as the load drops, the line voltage falls almost in the same proportion and the transformer core losses drop as well.

Since the maximum voltage exists only during a very small fraction of the year—when the maximum load occurs—it will be permissible to establish a materially higher value for the voltage than would be permissible in the normal constant potential system, no doubt at least 10 per cent higher. This means a valuable gain in capacity.

Many other important and interesting features might be considered, but space will not permit.

Any of the well known alternative forms of current-potential conversion units may be used in place of that shown here. In conclusion, it remains to emphasize the very great gain in capacity and stability offered by the constant current a-c transmission.

Very truly yours,

Percy H. Thomas (A'00, F'12)
(Federal Power Commission, Washington, D. C.)

Personal Items

Elihu Thomson (A'84, M'91, F'13, HM'28, past-president, and member for life) consulting engineer, General Electric Company, and director, Thomson Research Laboratory, Lynn, Mass., was awarded the medal of honor of the Verein Deutscher Ingenieure on the occasion of his eighty-second birthday in March 1935. The society which presents this outstanding award of the German engineering profession is the oldest and largest of engineering societies in the world, and the award has previously been conferred upon only 5 non-Germans, only one of whom, the late C. W. Rice (A'97, M'97, F'12) was an American. The citation read, "On Elihu Thomson, the great pioneer in the realm of engineering, the inventor and research scientist, the promoter of co-operation among engineers, there is conferred, on the anniversary of his eighty-second birthday, the V.D.I. medal of honor." Doctor Thomson was confined to his home by ill health, and the medal was accepted on his behalf by E. W. Rice, Jr. (A'87, M'88, F'13, HM'33, past-president, and member for life). Many honors and awards for his achievements have previously been bestowed upon Doctor Thomson, who was one of the founders of the General Electric Company and holds more than 700 United States patents. He was a vice president of the Institute 1887–89, and president 1889–90, later serving as a member of the Edison medal committee, 1910–15, and as representative on the United States National Committee of the International Electrotechnical Commission, 1914–30.

D. C. Jackson (A'87, M'90, F'12, past president and member for life) head of the department of electrical engineering, Massachusetts Institute of Technology, Cambridge, since 1907, will retire in June 1935. He was born at Kennett Square, Pa., and received the degree of civil engineer from Pennsylvania State College in 1885, subsequently taking 2 years of postgraduate study in electrical engineering at Cornell University. From then until 1889 he was vice president and engineer for the Western Engineering Company, Lincoln, Neb., engaged in the design and construction of electric light and power plants and distribution systems in that region. During 1889 and 1890 he was assistant chief engineer with the Sprague Electric Railway and

Motor Company, New York, N. Y., and the following year was chief engineer for the Edison General Electric Company, supervising in these positions the design and construction of many electric railway and power plants. The following year he formed a consulting engineering firm with W. B. Jackson (A'97, M'98, F'13, and Life Member) and also became professor of electrical

D. C. JACKSON

engineering at the University of Wisconsin. In 1907 he became professor and head of the department of electrical engineering at Massachusetts Institute of Technology. A partnership with E. L. Moreland (A'11, M'15, F'21) was formed in 1919, of which Professor Jackson was senior partner until 1930. The firm was particularly active in the field of railway electrification. Professor Jackson is at present Institute representative on the National Research Council and a member of the Institute's committees on standards, Institute policy, and legislation affecting the engineering profession, and has served on many others. He was a vice president of the Institute 1897–99 and president 1910–11. Among the honors which he has received is the Lamme medal of the Society for the Promotion of Engineering Education, of which he is a past-president. Professor Jackson is a member of a number of other technical societies in this and other countries, and is the inventor of a number of electrical devices as well as author of many papers and books on engineering subjects and engineering education.

E. L. Moreland (A'11, M'15, F'21) senior partner of the firm of Jackson and Moreland, consulting engineers, Boston, Mass., has been appointed head of the department of electrical engineering of Massachusetts Institute of Technology, Cambridge, to succeed D. C. Jackson (A'87, M'90, F'12, past-president, and member for life) who retires in June 1935. Mr. Moreland will also continue his affiliation with the engineering firm. He was born at Lexington, Va., and received the degree of bachelor of arts from The Johns Hopkins University in 1905. He then entered Massachusetts Institute of Technology, and graduated in 1908 with the degree of master of science. In this year he entered the employ of D. C. Jackson and W. B. Jackson (A'97, M'98, F'13, and Life Member), consulting engineers, as an assistant in their Boston office. In 1912 he was appointed manager of the office, and in 1916 became a partner. After overseas military service, Mr. Moreland formed the partnership with D. C. Jackson in 1919. The latter retired from the partnership in 1930. The firm has been engaged on many important engineering projects, including the electrification of the Great Northern Railway through the Cascades and the electrification of the Lackawanna Railroad. Many engineering studies for public utility companies have been made, including a study of electrical characteristics of transmission lines and generating stations for the Tennessee Valley Authority. Other projects on the development of power which have been studied have been in the petroleum industry and in connection with the proposed Passamaquoddy tidal power project in northern Maine. Mr. Moreland has been active in civic affairs and in the Technology Alumni Association, of which he becomes president this year, and now holds the rank of lieutenant colonel in the engineers, Officers Reserve Corps. In the Institute Mr. Moreland has presented several papers and has served on the electrical machinery and power generation committees, 1929–31; technical program committee, 1931–34; and Institute policy, 1933–34. He is now chairman of the standards committee, of which he has been a member since 1932, a member of the transportation

E. L. MORELAND

committee, of which he was chairman 1931–34, and Institute representative on the standards council of the American Standards Association. Among the organizations of which Mr. Moreland is a member are The American Society of Mechanical engineers, the American Society of Civil Engineers, the American Academy of Arts and Sciences, and the Boston Society of Civil Engineers.

J. J. Torok (A'27) former development engineer, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., has joined the research and development department of the Corning Glass Works, Corning, N. Y., where he will be concerned principally with insulators and allied products. Mr. Torok was born at Philadelphia, Pa., in 1903, and received the degrees of bachelor of science in mechanical engineering and electrical engineer from Pennsylvania State College in 1925 and 1928, respectively. In 1925 he entered the training course of the Westinghouse Electric and Manufacturing Company, and the following year was transferred to the high voltage laboratory in charge of impulse testing. In 1929 Mr. Torok developed a new type of lightning arrester now widely applied for transmission line protection. In 1933 he was transferred to the transformer engineering department in charge of special problems, and the next year he was transferred to the circuit breaker division in charge of lightning arrester development. Mr. Torok has written a score of articles and papers, some of which have been presented before the Institute.

J. T. Barron (A'07, M'20, F'27) who since 1926 has been general manager of the electric department of the Public Service Gas and Electric Company, Newark, N. J., has been named vice president in charge of electric operation. Mr. Barren graduated from the University of South Carolina in 1905, and after 2 years in the testing department of the General Electric Company at Schenectady, N. Y., entered the testing laboratory of the Public Service company at Newark. Shortly afterward he was assigned to the construction department, and in 1908 was made chief operator of substations and generating stations in the central division. In 1910 he became superintendent of this division, and in 1919 general superintendent of production, which title later was changed to general superintendent of generation. He was a member of the Institute's power stations (now power generation) committee 1919–24, and of the board of examiners 1929–30.

Marion Penn (M'21) who has been general superintendent of generation, Public Service Gas and Electric Company, Newark, N. J., has been appointed general manager. Mr. Penn is a graduate of Purdue University, class of 1911. He came to the Public Service Company from the General Electric Company at Schenectady, N. Y., in 1914, assuming the position of assistant division superintendent in the central division. During the war he was overseas, and shortly after his return became plant engineer at Newark in 1919. Following periods as chief engineer at various stations, Mr. Penn was promoted to general superintendent of generation in 1926. During the year 1927–28 he served as a member of the Institute's power generation committee.

C. S. McDowell (A'13, M'14, F'18, and past vice president) captain, U.S. Navy, and naval inspector of machinery, Camden, N. J., is now at the astrophysical observatory of California Institute of Technology, Pasadena, as supervising engineer for the construction of the 200 inch telescope there. Captain McDowell is a graduate of the U.S. Naval Academy, class of 1904, and has made various contributions to technical literature. He has been a member of the Institute's standards committee, the meetings and papers (now technical program) committee, the marine (now applications to marine work) committee, of which he served as chairman, and was a representative on

the U.S. National Committee of the International Electrotechnical Commission 1922–23. During 1920–21 he was a vice president of the Institute.

F. B. Jewett (A'03, M'10, F'12, and past-president) vice president of the American Telephone and Telegraph Company, and president of the Bell Telephone Laboratories, Inc., New York, N. Y., has accepted the position of national chairman of a campaign to raise a working capital fund of $161,000 for Engineering Index, Inc. The national committee, not as yet been completely enrolled, will endeavor to enlist the support of industry for the index and annotating service, discontinued a year ago as an activity of The American Society of Mechanical Engineers.

G. L. Knight (A'11, M'11, F'17) vice president, Brooklyn Edison Company, Inc., Brooklyn, N. Y., has been appointed chairman of the finance committee of United Engineering Trustees, Inc. Mr. Knight, who has served on a number of Institute committees and is now Institute representative of the board of United Engineering Trustees, Inc., was recently re-elected first vice president of United Engineering Trustees, Inc., as announced in Electrical Engineering for April 1935.

E. F. Smith (A'07, F'21) superintendent of substations, Commonwealth Edison Company, Chicago, Ill., retired in March 1935 after 41 years of service. He was a pioneer in operating procedure and safety practice in electrical substation work, with which he became identified early in his career when the substation system of distribution was adopted in Chicago. Mr. Smith served on many technical committees of the company and of the societies of which he is a member, and contributed a number of articles to the technical press.

H. R. Woodrow (A'12, F'23, and director) vice president in charge of electrical operations, Brooklyn Edison Company, Brooklyn, N. Y., has been appointed chairman of the real estate committee of United Engineering Trustees, Inc. Mr. Woodrow has served on a number of Institute committees, and is at present a member of the committees on publication, Edison medal, and economic status of the engineer, as well as Institute representative on the board of United Engineering Trustees, Inc.

H. P. Charlesworth (M'22, F'28, and junior past-president) assistant chief engineer, American Telephone and Telegraph Company, New York, N. Y., has been appointed a member of the Engineering Foundation committee on platform and general program. Mr. Charlesworth was re-elected recently as chairman of the board of Engineering Foundation as announced in Electrical Engineering for April 1935.

H. L. Hazen (A'26) assistant professor of electrical engineering, Massachusetts Institute of Technology, Cambridge, has been awarded the Levy gold medal of the Franklin Institute, which is given for outstanding technical papers appearing in the journal of the institute. The award was made to Professor Hazen "for 2 articles on the theory and design of servomechanisms, or devices for controlling the action of other machines."

Walter Breslauer (A'30) formerly public utility security analyst, Central Hanover Bank and Trust Company, New York, N. Y., is now an examiner for the Securities and Exchange Commission, Washington, D. C. Mr. Breslauer is a graduate of the University of Heidelberg and of the Technical College of Munich, and has contributed a number of articles on European utilities and electric transportation to publications.

A. G. Beljavsky (M'33) professor of electrical engineering at North-Caucas Institute of Energetics, Novocherkassk, U.S.S.R., recently was honored by his institution with a degree of doctor of technical sciences in recognition of his quarter century of faculty service and for his scientific and research work which has been principally in the field of a-c rectification.

J. W. Owens (A'10, M'20, F'27) former director, National Weld Testing Bureau, Pittsburgh, Pa., has accepted a position as director of welding with Fairbanks Morse and Company, Beloit, Wis. Mr. Owens was a member of the electric welding committee of the Institute 1927–31.

M. O. Evans (A'32) who was chief electrician and master mechanic with the Powhatan Mining Company, Powhatan Point, Ohio, has recently taken a position as electrical engineer with the Republic Steel Corporation, and is located at Uniontown, Pa.

V. R. Tate (A'28) formerly an electrical engineer in the patent department of the Minneapolis-Honeywell Regulator Company, Minneapolis, Minn., is now in charge of the patent department of Perfex Radiator Company and Perfex Controls Company, Milwaukee, Wis.

E. W. Grover (M'29) former assistant superintendent of substations, Commonwealth Edison Company, Chicago, Ill., has been appointed superintendent of substations to succeed E. F. Smith (A'07, F'21) who has retired.

R. U. Muffley (M'23) commercial manager, central district, Puget Sound Power and Light Company, Seattle, Wash., who recently became president of the Sales Managers Club in Seattle, has been elected to the board of trustees of the Seattle Chamber of Commerce.

W. J. Berry (A'31) former manager at Ashland, Kan., for the Western Telephone Corporation of Kansas has been transferred to Watonga, Okla., where he is manager of the Watonga, Canton, Seiling, Fay, and Greenfield exchanges of The Western Telephone Corporation of Oklahoma.

Edward Lipson (A'22) consulting and research engineer of Chelsea, Mass., is now research consultant for a laboratory maintained by a group of companies at Houston, Texas. Mr. Lipson has invented and patented various electrical, radio, and geophysical apparatus.

Samuel Ferguson (A'02) recently elected chairman of the board of directors of the Hartford Electric Light Company, Hartford, Conn., has been elected a member of the board of directors of the Arrow-Hart and Hegeman Electric Company.

H. J. Gille (A'01, M'13) manager, agricultural and industrial development, Puget Sound Light and Power Company, Seattle, Wash., was named president of the West Coast Mineral Association at its recent annual meeting in Seattle.

G. H. Gildersleeve (A'22) formerly district manager at the I-T-E Circuit Breaker Company at Cleveland, Ohio, is now connected with the Minneapolis-Honeywell Regulator Company with offices in New York, N. Y.

P. H. Trickey (A'30) who has been a design engineer with the Westinghouse Electric and Manufacturing Company, Springfield, Mass., is now a design engineer with the Diehl Manufacturing Company, Elizabethport, N. J.

C. H. Leatham (A'33) who has been sales research manager with the West Penn Power Company, Pittsburgh, Pa., is now with the Monongahela West Penn Public Service Company, Fairmount, W. Va.

O. L. Riggs (A'21, M'29) formerly assistant superintendent, has become superintendent of distribution in the electric department of the Lynn Gas and Electric Company, Lynn, Mass.

C. F. Osborn (A'24, M'31) formerly an electrical engineer with the Ralston Purina Company, St. Louis, Mo., is now with the Chandeysson Electric Company in St. Louis.

H. C. Fiske (A'24) former assistant chief engineer of the Jas. R. Kearney Corporation, St. Louis, Mo., is now with J. E. Sumpter Company, district consulting engineers, Minneapolis, Minn.

W. S. Barstow (A'94, M'99, F'12, and Life Member) retired, Barstow, Tyng and Company, Inc., New York, N. Y., was re-elected president of the Edison Pioneers at a recent meeting in New York.

F. L. Fuller (A'33) who has been an instructor at Stevens Institute of Technology, Hoboken, N. J., is now employed by the Western Electric Company at Kearny, N. J.

A. B. NEWELL (A'25) of Kirkwood, Mo., recently accepted a position as an assistant engineer with the Public Service Commission of Missouri, with headquarters at Jefferson City.

C. A. MULLEN (A'20, M'20) superintendent of southern division, Jersey Central Power and Light Company, who was formerly at Asbury Park, N. J., is now at Morristown.

STEFAAN PIEK (A'06) executive vice president, Syracuse Lighting Company, Inc., Syracuse, N. Y., has been elected a director of the Niagara Hudson Power Corporation.

WILLIAM KELLY (F'25) president, Buffalo, Niagara, and Eastern Power Corporation, Buffalo, N. Y., has been elected a director of the Niagara Hudson Power Corporation.

OTTO SNYDER (M'25) president, New York Power and Light Corporation, Albany, N. Y., has been elected a director of the Niagara Hudson Power Corporation.

W. E. STEWART (A'32) formerly assistant engineer at Nebraska Wesleyan University, Lincoln, is now engineer at radio station WOI, Ames, Iowa.

A. W. HAWLEY (A'30) Winsted, Conn., is studying for the degree of electrical engineer at the Yale Graduate School, New Haven.

E. R. RIETHMILLER (A'29) former chief engineer, Cardon-Phonocraft Corporation, Jackson, Mich., has engaged in consulting engineering practice.

E. A. SKONBERG (A'30) former sales manager, Electric Motor Repair Company, Springfield, Mass., is now with the Ekholm Corporation, engineers in Boston, Mass.

H. J. SMART (A'23) of Dalton, Mass., recently accepted a position in the engineering department of the Foxboro Company, Foxboro, Mass.

J. N. HELPBRINGER (F'26) electrical engineer, Ohio Electric Power Company, who was formerly at Sidney is now at Marion.

W. F. TURNER (A'25) formerly division manager, Wisconsin Power and Light Company, Madison, is now resident engineer for the company at Fond du Lac.

F. S. HIMEBROOK (A'32) is now an electrical engineer with the Master Electric Company, Dayton, Ohio.

R. E. SINCLAIR (A'31) Pacific Power and Light Company, has been transferred from Yakima, Wash., to Toppenish.

H. E. MORTIMER (A'33) Gulf States Utilities Company, has been transferred from Beaumont, Texas, to Port Arthur.

E. R. EVANS (A'20) Washington, D. C., has engaged in professional practice as a patent attorney and consulting engineer.

Obituary

KENNETH A. REED (A'19) chief engineer, electrical division, Hartford Steam Boiler Inspection and Insurance Company, Hartford, Conn., died March 23, 1935. Mr. Reed was born at Gregory, Ark., January 30, 1883. Following graduation from the University of Arkansas with the degree of bachelor of electrical engineering in 1907 he entered the apprenticeship course of the Allis-Chalmers Manufacturing Company at Cincinnati, Ohio. The next year he was employed in the operating department of the Northwest Water and Light Company, Yakima, Wash., and in 1910 joined the Westinghouse Electric and Manufacturing Company in St. Louis, Mo., as an electrical engineer. He was engaged in construction work until 1917, when he became assistant district superintendent. In 1918 Mr. Reed accepted the position of maintenance engineer in the electrical operating division of the Interborough Rapid Transit Company, New York, N. Y., where he had charge of the maintenance of central stations and substations. Leaving this position in 1921 and joining the Hartford Insurance Company, Mr. Reed assisted in the creation of the then new insurance of electrical machinery. His principal responsibility was the organization of an inspection service for electrical machinery that would minimize preventable losses, and papers on the subject written by him have been published in technical journals. At the time of his death Mr. Reed was a member of the electrical machinery committee of the Institute, on which he had served since 1931, and for several years he was a member of the electrical apparatus committee of the National Electric Light Association (now Edison Electric Institute).

RUDOLPH MELVILLE HUNTER (A'86, M'87, and member for life) consulting engineer and expert in patent cases, Philadelphia, Pa., died March 19, 1935. He was born at New York, N. Y., June 20, 1856, and received a mechanical engineering degree from Polytechnic College in 1878. In 1881 he organized an electrical manufacturing company, and also engaged in practice as a consulting engineer and electrical expert in patent cases involving infringement. Mr. Hunter was a prolific inventor, and ranked high among the world's inventors as a holder of patents, licenses for more than 300 of his inventions having been granted to the General Electric Company and the Westinghouse Electric and Manufacturing Company. Among the achievements credited to him may be mentioned a plan placed before the British Parliament for an electric railway for the proposed tunnel between Dover and Calais, 1883; the development of a submarine vessel, 1879–81; electric transformer system inventions sold to the Westinghouse company, 1886; the design and building of the first moving-picture projector in the world, 1894; and the organization, in 1889, of the Electric Car Company of America, of which he was at one time president. He was retained by the General Electric Company as an engineer and patent counsel for 22 years, and for 17 years was an acoustics expert for the Victor Talking Machine Company.

BURCH FORAKER (A'07) chairman of the board of directors, Michigan Bell Telephone Company, Detroit, died March 29, 1935. He was born at Hillsboro, Ohio, February 17, 1872, and studied at Ohio Wesleyan University and at Cornell University, where he was a member of the class of 1895. During summer vacation in 1893 he obtained employment as an installer with the New York Telephone Company, New York, N. Y., and decided to continue with that work. He later entered the engineering department, and from 1907 to 1912 was plant superintendent in the Brooklyn and Long Island areas. Following this Mr. Foraker was general superintendent in charge of plant construction and maintenance in the Manhattan, Bronx, and Westchester divisions. In 1924 he was appointed a general manager of the company with headquarters at Albany, N. Y., and 2 years later he was elected president of the Michigan Bell Telephone Company, holding this office until October 1934, when he became chairman of the board of directors. Mr. Foraker was a member of the Telephone Pioneers of America, and served as that organization's national president in 1930.

EDGAR FIELD PRICE (A'95 and member for life) vice president, Union Carbide and and Carbon Corporation, New York, N. Y., died April 15, 1935. He was born at Leaksville, N. C., in 1873. In 1891 he became connected with the Willson Aluminum Company, Spray, N. C., and it was here that the production of acetylene was noted when water contacted a charge withdrawn from an electric furnace after an attempt had been made to produce aluminum. When the Willson company retired from business Mr. Price joined the Westinghouse Electric and Manufacturing Company, and later he became connected with the Union Carbide Company, of which he rose to the presidency. In 1917, with the formation of the Union Carbide and Carbon Company, he became vice president, and was also an officer and director of some of the corporation's subsidiaries until his retirement in 1925. Mr. Price was decorated by the King of Norway in recognition of his interest in Norway's natural resources and the development of a water power system. He was a member of the Institute's electrochemistry and electrometallurgy committee 1914–16.

JAMES MARTIN KENT (A'21, M'21) teacher and engineer, Kansas City School District, Manual Training High School, Kansas City, Mo., died March 24, 1935. Mr. Kent first joined the Institute in 1900. He was born at Kewanee, Ill., October 6, 1865, and graduated from the University of Illinois with the degree of bachelor of science

in mechanical engineering in 1885. After short periods of employment he went to Kansas City in 1886 as superintendent of the public lighting plant of Sperry Associate Electric Company, and later became chief engineer of a private power plant, the installation of which he designed and superintended. In 1897 he accepted a position as teacher of steam and electricity and as designer and operator of the power plant in the Manual Training High School. In addition to this work he carried on a small practice as a consulting electrical and mechanical engineer, and during the period 1912–17 was president of the Henrici, Kent and Lowry Engineering Company, during which time he was largely responsible for the design and installation superintendence of a number of municipal and private plants. Mr. Kent was also a member of The American Society of Mechanical Engineers, American Society of Heating and Ventilating Engineers, Institute of Radio Engineers, American Chemical Society, American Electrochemical Society, American Association for the Advancement of Science, American Forestry Association, Society for the Promotion of Engineering Education, National Society for the Promotion of Industrial Education, National Educational Society, and Missouri Society of Mathematics Teachers.

Charles George Adsit (A'05, M'09, F'13, and past vice president) president, Des Moines Railway Company, Des Moines, Iowa, died March 27, 1935. He was born at Ironton, Ohio, November 1, 1874, and studied at the University of Chicago. After short periods of employment with engineering firms he entered the testing department of the General Electric Company at Schenectady, N. Y., leaving in the next year to go to Breckenridge, Colo., taking charge of the construction of a hydroelectric plant there. During this period he was employed by several mining companies, going to Bisbee, Ariz., in 1906 for railway construction. In 1911 he was employed by the Georgia Railway and Power Company on its development at Tallulah Falls, and subsequently was concerned with other developments of this company and its successor, the Georgia Power Company. Mr. Adsit resigned as vice president and consulting engineer of the company to engage in consulting engineering in Atlanta, Ga., until he became president of the Des Moines Railway Company in 1930. He was a member of the Institute's finance committee, 1922–23, and of the power transmission and distribution committee 1925–26; representative on the American Engineering Council, 1923–26; and a vice president of the Institute 1921–23.

Wilfred Thomas Birdsall (A'23) consulting engineer and physicist, Montclair, N. J., died March 16, 1935. He was first elected an associate member of the Institute in 1913. Mr. Birdsall was born at Philadelphia, Pa., February 29, 1888. In 1908 he received the degree of bachelor of arts from Amherst College, and in 1910 the degree of bachelor of science in electrical engineering from the University of Pennsylvania. For a short time in 1910 he was employed by the Telluride Power Company, Grace, Idaho, and then entered the Westinghouse Lamp Company, Bloomfield, N. J., becoming engineer in charge of the mercury arc rectifier department in 1912. In 1915 he became engineer in charge of research work, and the following year joined C. E. Knoepple and Company, industrial engineers in New York, N. Y. After overseas service he was employed by the Columbia Graphophone Manufacturing Company, Bridgeport, Conn., becoming general superintendent of the record division in 1920. He engaged in private consulting practice in 1921, and since then perfected and sold a number of inventions, including a type of fixed radio detector.

Edgar Allen Cerf, Jr. (A'27, M'33) assistant engineer outside plant bureau, Brooklyn Edison Company, Brooklyn, N. Y., died April 9, 1935, at Welland, Ont., Can., as the result of an automobile accident. He was born at Atlanta, Ga., March 5, 1905, and received the degree of bachelor of science in electrical engineering from Georgia School of Technology in 1925. The following year he received the degree of master of science in electrical engineering from Yale University, and the degree of electrical engineer in 1931. Mr. Cerf was employed in the electrical construction bureau of the Brooklyn Edison Company in 1927, and had been in the outside plant bureau since 1928.

Ernest White (A'31) assistant commercial engineer, Associated Telephone Company, Ltd., Long Beach, Calif., died recently, according to word received at Institute headquarters. He was born at Huntingdonshire, England, January 12, 1901, and studied at the University of California, receiving the degree of bachelor of science in electrical engineering in 1923. Until 1926 he was employed by the Southern California Telephone Company, Los Angeles, leaving at that time for graduate work at the University of Southern California. For a year he taught in the high school at Banning, Calif., and in 1929 entered the employ of the Associated Telephone Company, where he was engaged in planning and economic studies.

Torsten F. son Holmgren (A'04) consulting electrical engineer, Stockholm, Sweden, died in May 1934, according to word just received at Institute headquarters. He was born at Upland, Sweden, August 1, 1874, and graduated from the technical university at Stockholm in 1904. During 1894–97 he was employed by Siemens and Halske, Berlin, Germany, and from then until 1899 by an electric light company in Sweden. In 1901 he started practice as a consulting electrical engineer in Stockholm, at which time he was chief electrical inspector of the Swedish board of fire underwriters.

Alonzo Brackett Bradley (A'02) factory manager, Fibre Conduit Company, Orangeburg, N. Y., died March 2, 1935. He was born at Avon, N. Y., January 21, 1880, and received the degree of electrical engineer from Columbia University in 1903. He had held his position with the Fibre Conduit Company since 1920, previous to which he had been in various engineering companies, including B. F. Wood Engineers, Inc., New York, and in private practice as a consulting engineer.

Membership

Recommended for Transfer

The board of examiners, at its meeting held April 24, 1935, recommended the following members for transfer to the grade of membership indicated. Any objection to these transfers should be filed at once with the national secretary.

To Grade of Fellow

Cushing, Harvey M., chief engr., Buffalo Gen. Elec. Co., Buffalo, N. Y.
Gaylord, James M., chief E.E., Metropolitan Water District of Southern Calif., Los Angeles.

2 to Grade of Fellow

To Grade of Member

Albert, Arthur L., assoc. prof. of elec. engg., Oregon State College, Corvallis.
Balsbaugh, Jayson C., assist. prof., elec. engg. dept., Mass. Inst. of Tech., Cambridge.
Knipmeyer, Clarence C., head, elec. engg. dept., Rose Polytechnic Institute, Terre Haute, Ind.
Poole, Arthur B., E.E., The E. Ingraham Co., Bristol, Conn.
Smith, Don F., chief engr., Pacific Tel. and Tel. Co., Portland, Ore.
Van Ness, Bartow, Jr., E.E., Pa. Water and Pwr. Co., Baltimore, Md.
Whitehead, John H., lecturer in elec. engg., Constantine Technical College, Middlesbrough, Yorks, England,.
Woodyatt, James B., president and gen. manager, Southern Canada Pwr. Co. Ltd., Montreal, Que.

8 to Grade of Member

Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. If the applicant has applied for direct admission to a grade higher than Associate, the grade follows immediately after the name. Any member objecting to the election of any of these candidates should so inform the national secretary before May 31, 1935, or July 31, 1935, if the applicant resides outside of the United States or Canada.

Appleton, W. E., N. Y. & Queens Elec. Lt. & Pwr. Co., Flushing, N. Y.
Benoglou, G. D., 3951 Gouverneur Ave., Bronx, N. Y. C.
Blake, J. W., Fidelity & Casuality Co. of N. Y., Oklahoma City, Okla.
Brownlee, W. R., Tenn. Elec. Pr. Co., Chattanooga, Tenn.
Cain, D. C., Texas Elec. Serv. Co., Ft. Worth.
Castelin, L. P., N. Y. Pwr. & Lt. Corp., Albany.
Cooper, R. B., Oklahoma Gas & Elec. Co., Seminole.
D'Ippolito, M., P. O. Box 335, Dedham, Mass.
Downie, E. G., Gen. Elec. Co., Ft. Wayne, Ind.
Duehne, H. H. (Member), New York Central RR, New York City.
Ellmaker, H. C. (Member), Freeman Lang Studios, Los Angeles, Calif.
Emmerling, E. J., Union Gas & Elec. Co., Cincinnati, Ohio.
Fox, J. C. (Member), Virginian Ry., Narrows, Va.
Gakle, W. F., Kuhlman Elec. Co., Bay City, Mich.
Graham, W. F., Alabama Public Service Comm., Birmingham.
Hamilton, A. W., 3rd, Pa. RR., Washington, D. C.

Hastings, C. C., c/o R. E. Uptegraff Mfg. Co., Pittsburgh, Pa.
Hatz, E. W. (Member) Milwaukee Elec. Ry. & Lt. Co., Wis.
Hoadley, G. B., Mass. Inst. of Tech., Cambridge.
Homer, E. J., Morse Bluff, Neb.
Howell, A. H., Mich. Coll. of Mining & Tech., Houghton.
Hughes, P. H., N. J. Bell Telephone Co., Newark.
Kelley, F. B., Kansas City Pwr. & Lt. Co., Mo.
Koziol, R. J., 10 Brick Row, Southbridge, Mass.
Landis, G. G. (Member) Lincoln Elec. Co., Cleveland, Ohio.
Larson, N. G., Commonwealth Edison Co., Chicago, Ill.
Lemkin, H. J., F. A. D. Andrea, Inc., Woodside, N. Y.
Lozano y Vez, J., Gen. Elec. S. A., Mexico City, Mex.
Magann, J. W. (Member) Okla. Gas & Elec. Co., Oklahoma City.
McMynn, J. D., Consolidated Mining & Smelting Co., Trail, B. C., Can.
Melton, R. L., Carborundum Co., Niagara Falls, N. Y.
Miller, J. R., Board of Purchase, N. Y. City.
Mothersill, L. J. N., Polymet of Canada Ltd., Hamilton, Ont., Can.
Novak, L. C., Gen. Elec. Co., Lynn, Mass.
Paige, E. R., Cornell Univ., Ithaca, N. Y.
Pound, J. C., U. S. Army Engineers, Portland, Ore.
Redrup, A. F. (Member) 223 S. Washington St., Van Wert, Ohio.
Ricciardi, D., 718 Fairmount Pl., New York, N. Y.
Savage, C. F., Jr., General Elec. Co., Lynn, Mass.
Schmidt, A. J., Gen. Elec. Co., Schnectady, N. Y.
Simpson, H. B., Standard Varnish Works, Elm Park, N. Y.
Smith, H. K. (Member) Westinghouse Elec. & Mfg. Co., Chicago, Ill.
Smith, W. O., Long Island Ltg. Co., Glenwood Landing, N. Y.
Stoller, F. E., Cleveland Elec. Illum. Co., Cleveland Heights, O.
Thompson, C. V., 3820 N. 15th St., Phila., Pa.
Tompkins, G. H. (Member) N. Y. Air Brake Co., Watertown, N. Y.
Walker, E. T., Jr., Underwriters' Lab., Boston, Mass.
Wayman, J. B., So. Calif. Edison Co., Ltd., Los Angeles, Calif.
Wenz, R. C., Byllesby Engg. & Mngt. Corp., Chicago, Ill.

49 Domestic

Foreign

Alverson, G. D., U. S. Navy, Wailupe, T. H.
Chakravorty, S., Elec. Supply Co. Ltd., Gorakhpur, India.
Chopra, B. N., Renala Hydro Elec. Works, Punjab, India.
Dolan, H., (Member) English Elec. Co., Stafford, Eng.
El-Koshairy, M.A.B., City & Guilds Engg. Coll., London, S.W. 7, Eng.
Halton, G. H. (Member) Steatite & Porcelain Products Ltd., Stourport-on-Severn, Eng.
Ohri, S. R., Murree Elec. Supply Co., Ltd., Lahore, India.
Ranum, H., Cerro de Pasco Copper Corp., Oroya, Peru, S. A.
Sreenivasan, K. (Member) Indian Inst. of Science, Bangalore, India.
Tweedale, A. (Member) 7 Gordon Terrace Blackpool, Eng.

10 Foreign

Addresses Wanted

A list of members whose mail has been returned by the postal authorities is given below, with the address as it now appears on the Institute record. Any member knowing of corrections to these addresses will kindly communicate them at once to the office of the secretary at 33 West 39th St., New York, N. Y.

Dowty, Paul L., 1036 Sheridan Rd., Chicago, Ill.
Germenshausen, K. J., M.I.T. Dorm., Cambridge, Mass.
Golikoff, A., Main P. O. Gen. Del., Moscow, U. S. S. R.
Haddad, Raphael A., 500 Riverside Drive, N. Y. City.
Hansen, A. Fred, 2065 1/2 W. 30th St., Los Angeles, Calif.
Hope, Harry M., Belvedere, Calif.
Houston, Chas. E., 400—10th Ave., S. E., Minneapolis, Minn.
Phillips, R. M., 20 Garth Rd., Scarsdale, N. Y.
Rasmussen, David, 423 Hickory St., Ridgway, Pa.
Shelley, William L., 203 Greene Ave., Brooklyn, N. Y.
Smedley, A. B., 82 Warner Ave., Hempstead, N. Y.
Verrier, E. J., Anglo Newfoundland Dev. Co., Grand Falls, Newfoundland.
Watson, J. Connell, 69 Cambridge Terrace, London, W. 2, Eng.

13 Addresses Wanted

Engineering Literature

New Books in the Societies Library

Among the new books received at the Engineering Societies Library, New York, recently, are the following which have been selected because of their possible interest to the electrical engineer. Unless otherwise specified, books listed have been presented gratis by the publishers. The Institute assumes no responsibility for statements made in the following outlines, information for which is taken from the preface of the book in question.

TORSIONAL VIBRATION. W. A. Tuplin. N. Y., John Wiley & Sons, 1934. 137 p., illus., 9x6 in., cloth, $5.50. This book aims to give the designer of machines in which torsional vibrations are important an understanding of the methods for calculating them. The fundamentals of vibration theory which are necessary for a complete understanding of practical problems are explained and the procedure in actual calculations is set forth in detail. No extensive mathematical equipment is required of the reader.

TAXATION des RADIOTÉLÉGRAMMES. By Olivier. Paris, Librairie de L'Enseignement Technique, 1934. 61 p., 10x7 in., paper, 12 frs. This is one of 3 volumes which form a course of instruction in the operation of radio services upon ships and aircraft, intended for those preparing for this work as operators. The laws governing these services, the rates in force, and the duties of the operator are covered.

Great Britain. Department of Scientific and Industrial Research, REPORT of the RADIO RESEARCH BOARD for the period 1st January 1932 to 30th September 1933. London, His Majesty's Stationery Office, 1934. 137 p., illus., 10x6 in., paper, $.80 (British Library of Information, N. Y.). Among the topics discussed in this report are: the propagation of waves; directional wireless; atmospherics; electron oscillations giving rise to centimeter waves; radio-frequency standards; electrical measurements at radio frequencies; interference and receiver selectivity, the new transmitting installation at the National Physical Laboratory; time bases for use with the cathode-ray oscillograph.

ELECTROLYTES. By H. Falkenhagen, translated by R.P. Bell. Oxford (Eng.), Clarendon Press; N. Y., Oxford University Press, 1934. 346 p., illus., 10x7 in., cloth, $9.50. A systematic, comprehensive presentation of the modern theory of electrolytes, as developed by Milner and Debye and their co-workers. The book is a translation of the German original, which appeared in 1932, with revisions to include work done since that date.

EDISON, His Life, His Work, His Genius. By W. A. Simonds. Indianapolis and N. Y., Bobbs-Merrill Co., 1934. 364 p., illus., 9x6 in., cloth, $3.50. The author has carefully studied the collection of Edisonia at the Edison Institute, visited the scenes of Edison's life and consulted his associates widely. The result is an interesting book which corrects a number of current errors and legends and supplies a picture of the man and his work.

ELEKTRISCHE GASENTLADUNGEN, Ihre Physik und Technik. Bd. 2. Entladungseigenschaften technische Anwendungen. By A. v. Engel and M. Steenbeck. Berlin, J. Springer, 1934. 352 p., illus., 9x6 in., cloth, 33.50 rm. This is the second and final volume of a comprehensive review of the subject, the first volume of which appeared in 1932. The present instalment discusses the properties of the various forms of discharges that actually occur, together with their practical uses.

HANDBOOK of CHEMISTRY and PHYSICS, 19th ed. Ed. by C. D. Hodgman. Cleveland, Ohio, Chemical Rubber Pub. Co., 1934. 1933 p., tables, 7x5 in., lea., $6.00. A collection of tables, formulas, and other data frequently needed by chemists, physicists, and engineers. Fifteen important tables have been revised and 18 new ones added, among them one giving X-ray crystallographic data for about 1,300 elements and compounds.

HYDRAULICS. By E. W. Schoder and F. M. Dawson. 2 ed. N. Y. and Lond., McGraw-Hill Book Co., 1934. 429 p., illus., 9x6 in., cloth, $3.50. This is intended as a basic course in the hydraulics of engineering which will serve both as an introduction to specialized studies and a text and reference book. The physical phenomena of hydraulics are described, fundamentals are developed into useful formulas, and numerous examples of the analysis and solution of typical practical problems are given.

INTRODUCTION to MECHANICS and HEAT. By N. H. Frank. N. Y. and London, McGraw-Hill Book Co., 1934. 339 p., diagrs, 9x6 in., cloth, $3.00. This text represents the basic elementary course required at M.I.T. The course is intended to lay a thorough quantitative foundation, by a logical unified treatment of mechanics, acoustics, and heat, which will teach the student to appreciate and utilize fundamental and general methods of attack on problems in all branches of physics.

DIESEL ENGINEERING HANDBOOK (formerly the Diesel Power Plant Handbook). 7 ed. edited by L. H. Morrison and T. A. Burdick. N. Y., Business Journals, Inc., 1934. 320 p., illus., 12x9 in., lea., $5.00. A compendium of miscellaneous information upon the diesel engine and its uses. The basic principles are discussed, data are given on production and economics and modern designs are described. A chapter is devoted to super charging and scavenging, and another to lubricants and fuels. Oil purification is discussed. Other chapters consider plant planning, water cooling systems, diesel-electric stations, operation, maintenance, uses in transportation, etc. A catalog section closes the volume.

INTRODUCTION TO QUANTUM THEORY. By G. Temple. N. Y., D. Van Nostrand, 1934. 196 p., diagrs., 9x6 in., cloth, $3.75. Being intended as an introduction, the present book is more concerned with the historical and philosophical matrix of the theory than with the theory itself. It includes an account of the principle of duality and its implications in electromagnetic theory, the field theory of matter, quantum algebra, matrix mechanics, the relativistic wave equation, and the spinning electron.

PRACTICE of ABSORPTION SPECTROPHOTOMETRY with HILGER INSTRUMENTS. By F. Twyman and C. B. Allsopp. 2 ed. Lond., Adam Hilger, 1934. 140 p., illus., 10x6 in., cloth, 12s 6d. A guide for those commencing spectrophotometric work of extending it into unfamiliar fields. It introduces the theory of absorption spectra and describes various typical applications of absorption spectrophotometry, and discusses technique, including an account of the instruments developed by the publishers.

RIVETING and ARC WELDING in SHIP CONSTRUCTION. by H. E. Rossell. N. Y., Chicago, and San Francisco, Simmons-Boardman Pub. Co., 1934. 210 p., illus., 8x5 in., cloth, $2.25. The author discusses riveted and arc-welded joints from both the practical and theoretical points of view, with special reference to ship design and construction.

Industrial Notes

General Electric Sales Rise.—Sales billed by the General Electric Company for the first quarter of 1935 amounted to $40,393,538, compared with $34,935,551 for the same quarter a year ago, an increase of 16%, President Gerard Swope announced to stockholders of the company at their annual meeting on April 16. Orders received during the first three months this year totaled $49,379,932, compared with $38,148,654 for the same period of 1934, an increase of 29%.

Large U.S. Navy Order to Westinghouse.—According to a recent announcement, the Westinghouse Electric & Mfg. Co. has received a contract from the United States Navy Department amounting to approximately $1,750,000 for electrical equipment for eighteen 1500-ton destroyers. This apparatus consists of turbo-generator sets, regulators and switchboards which are to be installed in these new vessels now under construction. The equipment will be manufactured at Westinghouse plants in East Pittsburgh, South Philadelphia and Newark, N. J.

Heaviest Single-Car Shipment.—What is believed to be the heaviest single-car shipment ever made left the Schenectady Works of the General Electric Co. recently for its destination at the Potomac Electric Light & Power Co., at Bennings, D. C. The load consisted of a generator shaft, rotor and poles for a 25,000-kw frequency converter set, with a total weight of 367,000 pounds. The converter will be used to deliver 25-cycle single-phase power to the Pennsylvania Railroad. The freight car employed has a carrying capacity of 200 tons and alone weighs over 52 tons.

A New Electrical Equipment Sales Agency.—Announcement has been made of the formation of a new company, the Harris-Green Co., with headquarters in the Farmers Bank Building, Pittsburgh, for the sale of motors, control apparatus, transformers, line material, power factor corrective devices and similar materials used by public utilities, industrial and commercial establishments. The new firm is composed of G. N. Harris, with the Pittsburgh sales office of Westinghouse since 1929; J. G. Green, who was manager of the Westinghouse general industrial and resale sections at Pittsburgh; and Henry Harris, who organized and managed the United Electric Light Co., at Wilmerding, Pa., up to the time of its purchase by the Duquesne Light Co., in 1927, at which time he retired from active business.

Large Steel Mill Order to General Electric.—Included in an order amounting to more than $1,250,000 for new electric equipment to be furnished and completely installed by the General Electric Company at the Lackawanna plant of the Bethlehem Steel Company, are 7 d-c motors totaling 22,500 horsepower for driving the finishing end of Bethlehem's new continuous hot strip mill—one of the world's largest. This finishing end drive will consist of two 4500-hp and three 3500-hp motors, and one each of 2500-hp and 500-hp ratings. In addition, the order includes two 3-unit, 6000-kw motor-generator sets to supply power for the above motors; one 3-unit, 6000-kw motor-generator set to supply power to the drives of two tandem cold strip mills; the most modern ventilating system yet used in a steel mill motor room; and complete switchgear and control equipment for the preceding apparatus, including 19 metal-clad oil circuit breakers each with an interrupting capacity of one-half million kilovolt-amperes.

A New, Light Utility Truck.—The Four Wheel Drive Auto Company, of Clintonville, Wis., has introduced its new model HS into the line construction and utility field. This is of $1^1/_2$-ton capacity with the usual traction of four driving wheels. There are 46 lockers in the body to provide handy storage for all necessary tools and equipment. All compartments are covered by heavy doors and are weatherproof. The HS is powered with an 84-hp engine, and has four speeds forward and one reverse.

Trade Literature

Disconnecting Switches.—Bulletin 44. Describes outdoor, hook-operated disconnecting switches in ratings from 7500 to 69,000 volts. Pacific Electric Mfg. Corp., 5815 Third St., San Francisco, Calif.

Lightning Arresters.—Bulletin, 16 pp. Describes L-M valve-type, lightning arresters, types A, B, C, for the protection of distribution transformers, up to 15,000 volts. Line Material Co., South Milwaukee, Wis.

Metallic Zinc Powder. Bulletin, 16 pp. Describes the advantages of zinc dust paint as a primer and finishing coat for iron, steel and galvanized surfaces. Industrial applications, including several on electrical equipment, are illustrated. The New Jersey Zinc Co., 160 Front St., New York.

Armature Winding Machine.—Bulletin 201. Describes type 20 automotive generator armature winding machines. This equipment is largely automatic and is devised for large production numbers. The operator's skill is said to be a negligible factor in the operation of these machines. P. E. Chapman Electrical Works, 1820 Chouteau Ave., St. Louis, Mo.

Oil Aging Test Apparatus.—Bulletin, 4 pp. Describes the "Oxydator," an apparatus for determining the oxidability of lubricating and transformer oils, insulating compounds and varnishes, paints, etc., and indicating accurately their resistance to aging, to deterioration and life expectancy. Herman A. Holz, 167 East 33rd St., New York.

Wires & Cables. Bulletin LS-1, 4 pp., on the Vacuum Process Lead Sheath; Bulletin UC-1, 12 pp., on Non-Metallic and Metallic Armored Cables for direct earth installation, covering four general types—Trenchlay (non-metallic armored); Steel Taped Parkway (metallic armored); Lead Sheathed, with an outer covering of jute or saturated duck tape; Series Street Lighting ("Thiokol" sheathed). Bulletin WP-1, 4 pp., on Peerless Weatherproof Wires and Cables. Photographs illustrate specimens of this type of wire after 13 to 24 years of service. General Cable Corp., 420 Lexington Ave., New York.

Oil Fuse Cutouts.—Bulletin FC. Describes type "FC" subway oil fuse cutouts, available in two sizes for 2500 volts, 100 amperes, and 5000 volts, 200 amperes. A closed expansion chamber is used so that the cutouts are suitable for all subway installations and for locations exposed to corrosive fumes, explosive gases, salt air and inflammable dust. The larger size cutout clears 25,000 kva in $^1/_2$ cycle using modern accepted principles of arc quenching. Unit detachable sealed type potheads provide complete protection to the cable ends. The potheads are located on the bottom of the tank. This feature eliminates sharp bends of cable within the tank thus avoiding trouble due to surges. A comparatively narrow width of tank also results in less wall space being required. G&W Electric Specialty Co., 7780 Dante Ave., Chicago, Ill.

New General Radio Catalog.—"H," 188 pp. A comprehensive presentation of a wide line, including resistors, condensers, inductors, frequency and time-measuring devices, oscillators, amplifiers, bridges and accessories, standard-signal generators, oscillographs, cameras and analyzers, meters, power supplies, etc. A section on industrial devices appears in the catalog for the first time. Recognizing the fact that the application of electronic apparatus and technique, once confined to the communications industry, has rapidly invaded other fields, the company has extended its development program somewhat beyond the limits of the communication phase to include more general applications of electrical measurements. The instruments described in this section are the first result of this program. General Radio Co., Cambridge, Mass.

Voltage Regulation.—The Eight-Point Plan for Profitable Voltage Regulation. Consists of 9 bulletins and represents a comprehensive outline of voltage regulation for every vital point on a power system, from generator to consumer which, though long desired, was not previously economically justified. The devices described in this plan will provide efficient regulation at low first cost. The bulletins are numbered and titled as follows: GEA-2029- Generator-voltage Regulators; GEA-2054- Station-type Induction Voltage Regulators; GEA-2018A-Branch-feeder Induction Voltage Regulators; GEA - 2038A - Branch - feeder Step Voltage Regulators; GEA-2036A-Branch-feeder Step Voltage Boosters; GEA-1577B- Step Voltage Regulators for Higher-voltage Circuits; GEA-2055- Series Capacitors for Reducing Lamp Flicker; GEA-1971A- Autotransformers for Reducing Lamp Flicker. General Electric Co., Schenectady, N. Y.